Chapter 6
Innovation Fields for Sustainable Development of Wind Power

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Abstract This chapter intends to elucidate technical routes for sustainable development of wind power industry. However, the most prominent bottleneck for the target evidently comes from intermittent and stochastic source, which very likely causes extensive wind power curtailment. To cope with this challenging issue, the innovation technologies proposed in this chapter are generally divided into two categories: One is IT-based measures like integration operation (Sect. 6.1), intelligent wind farm (Sect. 6.2), and distributed and microgrid system (Sect. 6.3) to realize efficient and stable operation of wind power. Of course, diversified utilization such as heat supply, hydrogen production, and desalinization can also be regarded as one form of distributed utilization of wind power (Sect. 6.9). Another is associated with advanced design and manufacture technologies including design reliability (Sect. 6.4), turbine blade design and manufacture (Sect. 6.5), drive train system (Sect. 6.6), offshore wind power system (Sect. 6.7), and green manufacture (Sect. 6.8) so as to safe and clean utilization of wind power. All of these technical measures enable us to believe that it is possible to realize the utilization of wind power on a large scale to supply mankind with abundant green energy resources.

6.1 Integrated Operation Techniques of Large-Scale Wind Power

Generally speaking, wind energy resource is naturally of intermittency and randomness. And so the integrated operation of large-scale wind power is confronting varieties of challenges in prediction, control, and dispatch during the process of production, transportation, and consumption (Wang et al. 2014). The major obstacles in this regard are its safe and stable operation and dispatch (Zhang et al. 2010).

First of all, we know that the wind power resource is uneasy to estimate due to atmospheric disturbance and geographical variability. And yet the forecast of random and fluctuating wind power turns out even more difficult. As a result, it becomes a genuine obstacle to maintain power balance as the integration capacity of wind power is increasing dramatically.

In the meanwhile, the anti-disturbance capability of power electronic devices for over-voltage and over-current appears relatively weak. Most wind power equipments

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are vulnerable in the support capability for power grid as well. In particular, their electrical performances are remarkably different as compared with conventional generators. In case any faults such as short circuit occurs in power system, wind power immediately trips-off.

In addition, large-scale wind power in China is usually connected to the end of power grid nearby. The discrepancy between strong coupling of wind power units and weak supporting capability for power grid further aggravates control ability of large-scale wind farm stations/clusters. The voltage and frequency control in wind power system become a tough problem to guarantee safe and stable operation.

Finally, China's wind resource is mostly located in "Three North" areas, and "large-scale centralized development," "long-distance transmission," "multiple distributed integration," and "high penetration clustering development" are most salient features of China's wind power system. In contrast, wind power systems abroad belong to decentralized integration to low-voltage power grid and local accommodation mode. Furthermore, the power source in the northeast and North China area is dominated by coal-fired thermal power and lack of flexibility. Unreasonable power structure and insufficient peak regulation ability make it difficult to quickly response to external fluctuations in wind power generation. For instance, the proportion of flexible power sources like pumped storage and gas power in China merely amount to less than 5%. And the integrated wind power in the "Three North" area has exceeded 90% of China's total capacity, while its electricity consumption only reaches 23% of the total amount. Especially, the number of wind farm units of smaller capacity is much more than that of conventional power generators. As a result, power output exhibits strong correlation between adjacent wind farms. All of these factors could deteriorate coordinated operation between wind power, conventional power and power grid.

In a word, the power system in China is dramatically different from those in other countries in power grid condition, power source structure, load characteristics, and market mechanism. These factors seriously restrict the safe and stable operation of China's large-scale integrated wind power system. Obviously, it is an urgent task to resolve these power integration related technologies such as "precise prediction," "flexible control," and "intelligent scheduling." Hence, the capability of coordinated operation between large-scale wind power, conventional power supply, and power grid should be further upgraded to facilitate more stable operation and efficient utilization of large-scale wind power system.

6.1.1 Wind Power Prediction

By wind power prediction, we mean the establishment of a mathematical model to forecast the wind farm output based on ambient geographical information, weather parameters as well as operational conditions. Compared with conventional sources, wind farm output is primarily dependent on natural wind condition such as random and fluctuating wind speed and direction. Obviously, the wind power prediction can help to arrange conventional power generation, ensure safe and stable system operation, reduce spinning reserve, and enhance power system accommodation capability in order to guarantee economic and reliable operation of the power system.

The fluctuation of wind power can affect the operation of power system on three time scales. The first one is ultra-short-term fluctuation (within a few munities); the second is short-term fluctuation (a few hours to a few days) and the third is medium- and long-term fluctuation (weeks or months). Among them, the second one is vital in the power generation scheduling and short-term power balance, whereas the third plays its role in farm output prediction, power grid maintenance, and medium- and long-term electricity planning and transaction.

According to above-mentioned time scales, wind power prediction can be divided into ultra-short-term, short-term, medium-, and long-term predictions. Under normal circumstances, the prediction of no more than 4 h can be regarded as ultra-short-term prediction; as for shorter prediction with minutes, it is mainly used for wind power control, power quality assessment, design of wind turbine components, etc. Short-term prediction means prediction within 0–72 h, while the wind power prediction of medium and long terms mainly refers to the prediction weekly, monthly, quarterly, and even longer periods.

In order to reflect the variation of atmospheric circulation during wind source and wind power prediction, wind speed and direction data by NWP are input at first. The wind source prediction is a computer simulation technology to analyze temporal and special variations in wind energy. The main point is to have precise atmospheric circulation data and understand its fluctuation mechanism. On the other hand, the wind power prediction is also a computer simulation technology to provide high-precision temporal output of a wind farm. In order to lessen its uncertainty, we need to enhance the adaptability of software for various wind farm conditions. In summary, we would pay equal attention to both the estimation of wind energy resources and the prediction of wind power output, focusing on the mechanism in the variations and fluctuation of wind speed and direction.

1. **Technical status and requirements**

The research and application of wind power prediction abroad are started in the 1990s; physical, statistical, and hybrid methods were widely applied in succession (Hodge and Milligan 2011). They have exerted more apparent influences on power system operation when the large-scale centralized integration of wind power system is completed in recent years. The research focused on wind power prediction has gradually shifted to consideration of complex topography, extreme weather events, and offshore environment. The following prediction algorithms are put forward: the method based on the coupling of medium- and small-scale numerical model, onshore wind power clustering prediction method with multi-numerical weather forecast sources, and offshore wind power prediction method coupled with the atmosphere and ocean models.

In recent years, wind power prediction has made rapid progresses in China. Nevertheless, the limited historical data accumulation, frequent curtailment of wind power, complicated topography, and various climate types prevent us to directly use predic-

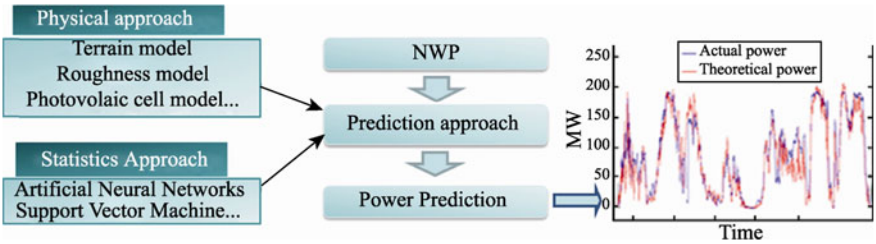

Fig. 6.1 Wind power prediction

tion technology and software available. Hence, domestic universities and research institutes have carried out a series of works on the wind power prediction, aiming at developing prediction mode and understanding wind power character. A statistical prediction method with multiple measured data and a regional prediction method based on linear rising time scale of wind farms are put forward. As for wind power prediction, a physical prediction method based on CFD model and an adaptive configuration coupling statistical prediction method have been proposed (Fig. 6.1), which greatly improved the adaptability of wind power prediction and promoted the rapid application of wind power prediction technology in China (Feng et al. 2010). As input data for wind power prediction, NWP is the most important factor affecting its accuracy. It is regarded as a main way to improve the precision of numerical prediction by accurate simulation of changing process of boundary meteorological elements. At present, researches on NWP are mainly concentrated on the dynamic downscaling technology of middle- and small-scale numerical coupling mode, rapid assimilation technology based on wind farm meteorological observation.

At present, China's wind power prediction system in both grid side and wind generation side has been established and applied in the major provinces with wind power integration. The predicted precisions vary from areas to areas. As compared with most advanced software, there still leave some spaces for further improvement. On the other hand, changeable wind conditions, extreme weather events, large-scale cluster wind power generation, etc., also constitute great challenges to the high-precision prediction of wind power in China. In regard to wind power prediction models associated with complex terrain, extreme weather, and offshore wind field, they are still immature and need further improvements.

2. **Technical trends**

With the increasing of wind power integration in the future, the absolute errors in wind power prediction would be far greater than the deviation in power demand because of uncertainties in load prediction. Hence, wind power uncertainty is an important risk factor for power system operation. For this reason, the safe and stable operation of power system presents higher requirements in the prediction resolution and precision. And thus, numerical simulation should be correspondingly improved according to the application requirements in the flexibility and adaptability of wind power prediction.

As hot topics in wind energy and wind power prediction, the European Union has ratified a research project on “the next-generation wind power prediction technology suitable for large-scale integration” to express their continuous support to the wind power prediction research. The project is mainly concentrated on probability prediction, event prediction, and high-precision numerical weather prediction technologies. Xcel and NCAR in USA jointly developed an integrated system considering the interaction of wind power station monitor and numerical weather prediction. According to the application requirements and research progresses, the development of wind resource simulation and wind power prediction is toward detailed simulation and custom-made prediction, multi-space and multi-time scales, multiple objects, high resolution, high precision, probability prediction, and extreme weather event prediction.

In terms of wind resource numerical simulation, wind power prediction and customized meteorological applications put forward higher requirements for researchers. Based on the observational data of multi-dimensional wind energy resources, the main factor for improving weather forecast is to accurately simulate the distribution and evolution of elements in meteorological boundary layer. The directions in the simulation of wind energy resource distribution in the boundary layer are: the formation mechanism and prediction method of sudden weather events, the fast assimilation method of multi-dimensional observation data, and the optimization of boundary layer parameterization scheme. In addition, with the dropping of the computer hardware cost, the ensemble prediction technology depending on consumption of computing resources to achieve better forecasting of high reliability is also a research trend.

In terms of wind power multiple temporal and spatial scale prediction, the prediction method based on single wind farm couldn’t meet the requirement of fast coverage any more with the construction of large wind base. Moreover, the timelines and accuracy of the prediction model are unable to satisfy the needs in application as well. The clustering prediction method considering the spatial and temporal correlation mechanism of large wind farm clusters will become a significant direction; considering the decentralized wind power prediction, the intelligent modeling with online optimization features becomes a potential trend. Finally, the multi-time scale dynamic optimization method based on big data technology along with the accumulation of operational data will become a new trend.

In terms of wind power probability and event prediction, the traditional deterministic scheduling method is no longer suitable for economic dispatch and risk assessment due to lack of evaluation capability in predicting power uncertainty. In this case, the probabilistic prediction technology is usually relied on for scheduling evaluation. The fluctuation of large wind bases output will cause huge risk on the safe operation of power system; the accurate prediction of these high risk events will also become a pressing topic in the future.

3. Key technologies

(1) Wind resource numerical simulation and prediction

To overcome the shortcomings in the conventional weather forecast such as low resolution in the boundary layer for wind resources numerical simulation, inadequate adaptability for the forecasting requirements, long assimilation period, etc., it is necessary to establish a technical system capable of the custom-made wind resource numerical simulation and wind power prediction. The future research contents in this regard include: ① distribution mechanism and prediction of wind resource in boundary layer and ensemble forecasting technology suitable for wind power probabilistic prediction; ② formation mechanism and prediction method of abrupt weather events causing wind power ramp; ③ NWP dynamic downscaling technology reflecting local effects of wind farms; ④ numerical prediction technology with online interaction and real-time assimilation of wind farms; ⑤ dynamic coupling technology of marine meteorology model.

(2) Wind power multiple temporal and spatial scale prediction

Considering the rapid development of large-scale wind power, it is needed to study wind power prediction algorithm system suitable for multiple scenarios. The future researches include: ① wind power statistical prediction theory based on big data analysis; ② wind power physical prediction method based on micrometeorology; ③ wind power coupling prediction method based on multiple methods application; ④ wind power prediction method under special conditions such as curtailment; ⑤ wind power prediction intelligent modeling and online optimization; ⑥ prediction method suitable for distributed wind power; ⑦ wind power ultra-short-term prediction method based on multi-dimensional monitoring data; ⑧ correlation mechanism of wind energy resources and prediction method for large wind power clusters; ⑨ ultra-short-term prediction method of wind power independent of real-time observation data; ⑩ wind power prediction method under the power market; ⑪ wind power prediction method considering the coordination of wind power and energy storage; ⑫ offshore wind power prediction method based on NWP.

(3) Wind power probability and event prediction

In order to meet the demands of power grid optimal dispatch and operation, risk assessment of large-scale wind power integration is necessary to carry out the researches on wind power probabilistic prediction and event prediction; future research contents include: ① wind power probability prediction method based on NWP forecast; ② wind power probability prediction theory and method considering the uncertainty of NWP; ③ probability prediction method for wind farm/wind power clusters with strong correlation; ④ mechanism of rapid and wide range fluctuation of wind power output and ramp events prediction; ⑤ prediction method of wind farms trip-off by gusty wind.

6.1.2 Integrated Operation and Management

Wind power integration control means the realization of flexible response and active support of large-scale wind power to power system dispatching orders by active/inactive power control, frequency/voltage control, fault crossing control, inertia control, and other technical measures in wind power unit, wind farm station, and wind power cluster. Due to low energy density of wind energy resources, the capacity of wind units is only a few hundred to several thousand KW, much lower than the capacity of conventional thermal and hydro unit of hundreds of MW order. Therefore, thousands or even tens of thousands of wind units, complex gathering system, and multi-level boost for wind power system are required to achieve large-scale wind power grid integration and long-distance transmission. The stochastic fluctuation of wind energy resources and the application of large number of power electronic interface devices render the wind power system quite different from the traditional power supply. Due to the lack of inertia and weak overload capability for power electronic devices, wind power equipments exhibit poor performance to resist grid disturbance and weak support capability for power grid. In addition, the operation control needs to consider the coordination of many power generation equipments. With the growing of the proportion of integrated wind power capacity, the control of wind farms is mostly passive and the control performance is uneven. So the large scale of wind power integration into the weak power grid can cause a series of problems such as voltage instability, frequency instability, sub-synchronous oscillation, and harmonic resonance. Moreover, the large wind bases in Hexi Corridor, Xinjiang, Hami, Mengxi, and northern Hebei are usually located at the end of the power grid, where the grid structure is weak and the short-circuit capacity is small. Namely, large-scale wind power is integrated into a terminal of weak power grid, thus drastically deteriorating the capability of wind power control.

1. **Technical status and requirements**

Wind power in Germany, Denmark, and other countries are generally integrated into a relatively close and strong power grid, and the distribution of wind power and load are uniform. No large wind base of ten million kW there is integrated into terminal power grid. Therefore, only the characteristics of a single wind power unit and control strategy are studied. They haven't yet paid attention to the interaction between wind power units and power grids, adaptability, active control, etc.

In the field of electromechanical and electromagnetic transient wind turbine modeling, breakthroughs have been made in these countries and the accuracy is satisfactory. The results were applied to analyze the output characteristics and control methods for single units. There are also numerous demonstrations in the field of energy storage to enhance wind power output characteristics, improve wind power fault ride-through capability, perfect wind power and energy storage joint control, and optimize management. However, most of them are based on a specific scenarios and do not have any extension possibilities. The researches on the mechanism of cascading failure caused by power grid disturbance, harmonic production, and prop-

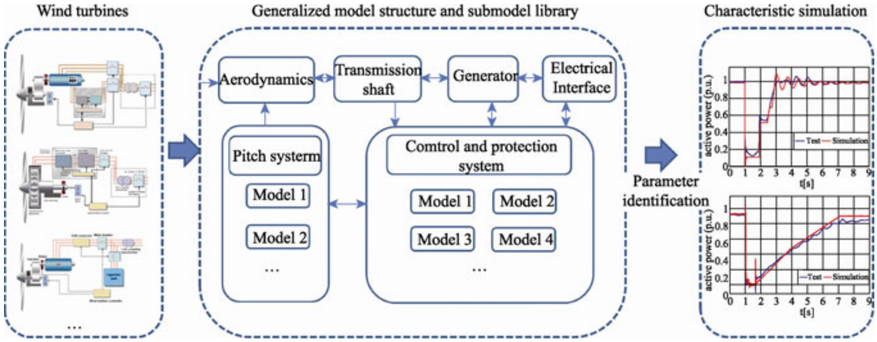

Fig. 6.2 Wind turbine generalized model and operation characteristic simulation

agation mechanism, and the control strategy of large-scale wind power unit under different power grid intensity have not been studied yet at home and abroad.

The wind power development in China, however, is dominated by large wind clusters integrated into high-voltage grid and long-distance transmission. In recent years, domestic research institutions and universities have conducted lots of research in this field and obtained a series of innovative achievements, including wind turbine modeling and integration operation simulation (shown in Fig. 6.2), and the interaction influence of large-scale wind power and power system. Regarding large-scale wind power trip-off, its origin and suppression measures of large-scale wind power cascading failures were carried out based on the actual fault data and repetition simulation; and the researches on the energy storage to enhance the wind power grid adaptability have provided technical supporting for the safe and stable operation of large-scale wind power integration. In addition, demonstrations for jointly operation of wind power and energy storage are also conducted, which promote the development and application of energy storage in renewable energy.

2. **Technical trends**

At present, the hot topic in the wind power control area abroad is mainly concentrated on fault ride-through control strategy, virtual synchronizer technology, etc. However, nine large wind bases at the level of thousands MW have been built in China. The fact means that we should consider problems in the large-scale development mode. The voltage of tens of thousands generating units needs to be boosted more than 1000 times through multiple level transforms, the electricity transmitted thousands of kilometers distance, and wind power units integrated into power grid. The electrical distance between wind power units is only a few hundred meters exhibiting strong correlation, while the electrical distance between the wind farm and the power system can be more than 100 km with weak support characteristics. All these characteristics result in that the operation of wind power can be easily damaged by power grid disturbance and failure. They are unable to provide strong support for stable operation of power grid. The issues such as the interaction mechanism and cascading failure of large-scale wind power units can’t be avoided by modeling and simulation up to now, which becomes a great challenge for the operation of large-scale wind power integration. Therefore, an in-depth study on the following problems such as destruction mechanism of wind power, wind power operation mode, wind power unit active control for grid adaptively, wind power testing method, and the active coordination control of energy storage should be put on agenda so as to enhance the effective support of wind power system to safe and stable operation in the power grid.

In terms of large-scale correlation characteristic and operation state destruction mechanism, for the power grid with high-proportion wind power, on the basis of the analysis of the traditional power system safety and stability mechanism, it is necessary to study the correlation characteristics between the power generation unit and the power electronic equipment in the large-scale wind power cluster integration area, as well as the wind turbine trip-off spread and evolution mechanism disturbance. When subjected to disturbance.

In terms of wind power unit active control for grid adaptively, it is an important trend in the future to enhance the active supporting capability of the wind power unit and stations on power system voltage/frequency/inertia/damping. Meanwhile, with the offshore wind power and onshore large wind clusters development, traditional AC gathering cannot meet the requirement for the safe and stable transmission, the large-scale wind gathering mode will be toward multiple level voltage hybrid AC/DC mode, and its operation control will be next technical trend.

In terms of wind coordination control for wind power and energy storage, it is needed the study of large-scale energy storage enhancing wind power fault ride-through capability, using energy storage system to control the wind farms power quality such as harmonics and flickers, using energy storage to support wind power distributed integration. With the progress and application of the energy storage technology, it will become new technical trend of using energy storage to enhance the wind power active control performance.

In terms of wind power control experimental demonstration technology, it is needed the study of the empirical method for wind power safe and stable integration mechanism and intelligent control, simulation of grid operation characteristics with controllable voltage/frequency/impedance, wind power/energy storage facilities, AC/DC gathering system integration operation testing and verification, etc.. It will be main technical trend of wind power control empirical demonstration technology of discovery large-scale wind power interaction mechanism and operation performance, verify wind power active control for grid adaptability, coordination operation and control strategy for wind power and energy storage.

On the whole, wind power integration control will be toward grid friendly, active supporting, adaptively control and clustering control, wind power DC gathering/grid/transmission will be a new development trend. In the future, wind power will be gradually with the capability of active supporting the power system voltage and frequency regulation, realize wideband oscillation suppression, support system failure recovery and black start, so as to achieve and exceed the conventional grid control performance of synchronous generators in some indexes.

3. Key technologies

(1) wind power operation state destruction mechanism

Through the study of wind power coupling characteristics and interaction laws with the weak support power grid, the propagation, amplification, and the cascading trip-off evolution mechanism after the wind units disturbance can be revealed, the future researches mainly include: ① wind power output characteristics and control system stability domain under complex grid conditions; ② large-scale wind power transient response characteristics with weak power grid support; ③ research on the interaction and influence between large-scale wind power units and wind farms/clusters, reveal the operation destruction mechanism of large-scale wind power systems; ④ the reaction and evolution mechanism of wind power cascading trip-off caused by power grid disturbance/fault; ⑤ the generation, propagation, and amplification mechanism of wind power harmonic, flicker, etc., as well as the coupling performance and influencing factors for power quality.

(2) active control for wind power integration

Through the study of the control strategy of the wind power unit under the complex power grid and the control method of the active support for the weak grid, the anti-disturbance capability of the unit and the active support capability for the power grid of the wind stations are improved. In the future main researches include: ① online identification technology of wind unit key parameters and power grid characteristic; ② active support technology of large-scale wind power for power system voltage/frequency/inertia/damping; ③ wind station reactive power optimization and control technology based on its dynamic and static reactive ability; ④ large-scale wind power fault ride-through technology; ⑤ voltage and frequency adaptability technology for large-scale wind power integration; ⑥ real-time situational awareness and coordinated protection and control technology for large-scale wind power base; ⑦ voltage source synchronous integration technology of large-scale wind power under weak grid conditions; ⑧ adaptive power quality control technology for wind power integration; ⑨ AC/DC hybrid gathering and operation control technology for large-scale wind farms with multi-voltage levels; ⑩ power quality intelligent regulation technology for wind power integration system in the user side; ⑪ an experimental demonstration technology for intelligent control of wind power integration and operation.

(3) coordination control of wind power and energy storage

Through the studies on the joint operation and control technology for wind power stations and energy storage system, the transient stability performance of wind power stations can be enhanced, and the large-scale wind power safe operation can be ensured. In the future main researches include: ① joint operation and control technology for large-scale energy storage and wind power; ② using energy storage to enhance the wind power fault ride-through capability; ③ power quality active control technology based on energy storage system, such as wind power harmonics, flicker, reactive power, frequency deviation regulation, etc.; ④ large-scale wind power active participation in power grid regulation technology cooperated with energy storage; ⑤ self-starting operation and control technology for joint wind power and energy storage; ⑥ distributed wind power integration and operation technology based on energy storage application.

6.1.3 Optimal Dispatching and Risk Prevention

Wind power output is always accompanied by strong fluctuation and uncertainty, which brings about inconvenience in dispatching control and risk prevention, for instance, the stochastic fluctuation and anti-peak regulation performance of wind power would affect the peak load regulation of power system (Faried et al. 2013). Since wind power is hard to forecast, thus bringing about difficulties for power system scheduling. Large-scale wind power is usually integrated into the end of power grid and needs long-distance transmission, leading to uncontrolled voltage stability. In order to overcome the uncertainty of large-scale wind power, it is necessary to reserve enough backup power and regulation capacity so as to ensure user-side power supply when wind power is insufficient. The traditional power source should be reduced to a certain amount to ensure energy balance and frequency stability in the power system. Therefore, wind power optimal dispatch means to arrange the traditional unit commitment, generation plan, tie-line operation mode, etc. We need to set aside reserved space for wind power accommodation, analyze, and foresee potential safety issue and its impacts on power system. We had better take active prevention measures for safe and stable operation and maximize the utilization of wind power. In a word, the implementation of optimal scheduling and risk prevention is the main point to ensure the safe operation and efficient utilization of wind power.

1. **Technical status and requirements**

Wind power dispatch in Denmark, Germany, Spain, and other countries with high proportion of wind power integration is implemented based on power market. All of wind power and conventional power participate in the power market and obey the relevant rules. Through the multi-time scale market rolling transaction such as day-ahead, intra-day, reserve service, ancillary service, etc., along with the corresponding price mechanism, the uncertainty risk of wind power is controlled in the safety range. In Europe and America, there is seldom wind power curtailment due to abundant flexible adjustment power source in the system such as gas generation units and hydropower. At present, the flexible source capacity in Denmark, Germany, and Spain is much more than wind power. And it is also possible to coordinate the flexible resources in neighboring countries or regions through power market mechanism so as to realize the maximum accommodation of wind power. In addition, these countries are also paying attention to the technology innovation such as energy storage and electric vehicles by joint operation of energy storage and wind power. In this way, the fluctuation of wind power could be mitigated by maximizing of wind power accommodation.

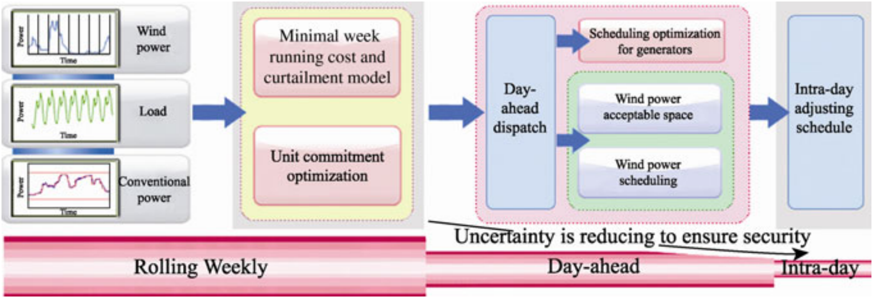

Fig. 6.3 Wind power optimal dispatch

With large proportion of fossil power, China is lacking in flexible power sources together with imperfect power market mechanism; objective conditions and operation mechanism for wind power accommodation are quite different from above-mentioned countries. Hence, their experience cannot be directly borrowed. In wind power optimal dispatch, a large number of researches have been done in domestic research institutions and universities. According to the power system operation mechanism and power structure in China, an uncertain operation regions' dispatching method by incorporating wind power prediction into system dispatch as shown in Fig. 6.3 is proposed. The multi-time scale wind power optimization scheduling model and technical support system based on power prediction have also been applied in the "Three North" area, which have effectively improved the capability of wind power accommodation (Liu et al. 2014). In order to reduce the influence of fluctuation and uncertainty of wind power on the safe operation of the power grid, the active and passive power control of wind/solar/energy storage generation unit and its coordination operation and control with power grid is studied. The results have supported to set up a national wind/solar/energy storage/transmission demonstration project aiming to explore operation characteristics, energy storage, and its joint dispatching control of wind power. However, the curtailment of wind power remains a serious problem in short term due to the power supply and power grid structure characteristics in China. Optimal dispatch technology needs further improvements. The stochastic planning and risk prevention technology accounting for wind power uncertainty need further breakthrough.

2. **Technical trends**

In the future, it is estimated that the proportion of renewable energy could exceed 50% in some provinces of the "Three North Region." The stochastic fluctuation and uncertainty of large-scale wind power would directly affect the power system operational reliability. The power system with high proportion of wind power would be facing huge operation risk, and the regulation capability of the traditional coal power is unable to meet the demand of fluctuation mitigation of large-scale wind power system. In addition, there are thousand and hundreds of wind power stations integrated into the power grid. Still the correlation between the power stations is strong, the dimension of the optimal scheduling problem with correlated random variables can reach millions level, and the solution becomes extremely complex at the moment. The globally optimized stable and reliable solution for complex systems with high dimensional variables has not been realized yet thus far. Therefore, the optimal dispatch method of wind power can be aimed to solve uncertain scheduling, energy storage joint dispatch, online risk forecast, and active prevention.

In terms of correlated wind power stochastic optimal dispatch technology, the correlation between wind farm generations has shown unsteady characteristics according to the weather conditions. We need to carry out researches on the formulation of multi-temporal and -spatial correlation of wind power, and power system analysis, considering the correlation and uncertainty of wind power. In addition, because of the complexity of the optimization problem with correlation variables, it is urgent to present a theory and corresponding algorithm for wind power stochastic optimal dispatch with strong correlation, so as to realize the globally optimal scheduling and the maximal accommodation of wind power.

In terms of joint dispatch of wind power and energy storage in the future, smart grid can be regarded as a large number of energy storage units such as energy storage stations, pumped storage, electric vehicle, etc. It is necessary to study the following topics such as optimal capacity allocation method, decentralized autonomous and centralized coordination optimization method, multi-time scale joint operation method of wind power and energy storage system to maximize benefit and improve reliability of power system of this sort.

In terms of risk evaluation of large-scale wind power operation and active prevention to cope with the risk caused by high proportion of stochastic wind power, it is urgent to carry out optimal allocation and multi-level reserve method research for energy storage by establishing wind power operation risk warning model. Then, the risk can be quickly identified online and actively prevented by urgent energy storage.

On the whole, the optimal dispatch of future large-scale wind power will be directed toward market operation, stochastic optimal scheduling, cross-provincial and cross-border transaction, online risk assessment, and active prevention.

3. Key technologies

1) Stochastic optimal dispatch

In order to cope with the optimal dispatch problem for uncertain wind power, the stochastic modeling with strong correlation and its fast algorithm need to be studied. In the future main research subjects are: optimal scheduling decision theory considering uncertainties in wind power prediction; α[1] stochastic optimal scheduling technology for wind farms with correlation; β stochastic programming method and fast solution technology for uncertainty and correlation coupling of large-scale wind power; χ stochastic optimal scheduling model considering wind power prediction uncertainty and solutions based on scenario reduction; δ large-scale wind power stochastic unit commitment and parallel solution technology; ε power system analysis method considering the correlation and uncertainty of wind energy resources.

[1] α→①, β→②, γ→③, δ→④, ε→⑤

2) Multi-space and multi-time optimal dispatch

In order to solve the problem of large-scale wind power integration dispatch and utilization, research on optimal dispatch technology of wind power in different time and space scales is needed. In the future main research directions include: the short-term optimal dispatch method of wind power considering its uncertainty, put forward the short-term optimal dispatch region and rolling correction method; α[2] wind power medium- and long-term generation planning method considering the randomness with restrains in power system security and stability; β the dynamic reactive voltage stability control technology for large-scale wind power centralized integration area based on model verification, to ensure the security of the power grid operation with the large-scale wind power integration; χ the optimization dispatch technology based on UHV cross-province and cross-border accommodation, to support the multi-time scale coordinated scheduling, transaction and optimal accommodation of large-scale wind power across the provinces, and improve wind power utilization efficiency. δ girding optimal dispatch and intelligent control technology for distributed large-scale wind power supporting whole system operation, provide dispatching technology, to support large numbers of high-proportion decentralized wind power integration.

3) Multi-energy joint dispatch

In order to solve the joint operation of different energy types such as large-scale wind power, conventional power, and heat energy to promote the efficient utilization of wind power, the joint optimization scheduling technology should be carried out considering the complementarity of wind power and other energy types. The directions of future researches include: the joint operation technology of large-scale wind power and heating system, which can realize its joint optimal operation. α[3] joint optimal scheduling technology for multi-energy complementary system including wind, solar, hydro, coal power, etc.; β multi-time scale rolling coordinated scheduling and control method for large-scale wind power, solar power, and energy storage system; χ optimal design and control technology of smart microgrid with multi-energy complementary operation including decentralized wind power; δ multi-energy of wind and pumped storage joint optimal scheduling and operation technology based on marked mechanism.

4) Risk prediction and active prevention

Aiming at the increasing operational risk of power system with high-proportion wind power integration, it is necessary to carry out the researches on coupling mechanism of wind power operation and active defense measures such as energy storage. Future major directions include: multiple operational risk coupling mechanisms such as extreme weather, wind power prediction uncertainty, and cascading faults in power grids; α[4] optimal multi-level reserve capacity allocation and emergency control technology for large-scale wind power multiple risks; β energy storage optimal allocation

[2] α→①, β→②, γ→③, δ→④

[3] α→①, β→②, γ→③, δ→④

[4] α→①, β→②, γ→③, δ→④, ε→⑤

and control technology in case of large-scale wind power operation risk; χ the role of different energy storages in wind power operation risk and emergency control technology; δ large-scale wind power operation risk evaluation and pre-warning technology; ε quick online risk identification method for multiple wind power uncertainties; ϕ active defense method for cascading failure risk of wind power base.

6.1.4 Concluding Remarks

The fluctuation of large-scale wind power and wide application of electronics technology in wind power integration and transmission render future power system evolve into a new form of system with high proportion of renewable energy and advanced electronics domination. Then, the operation performance of power system could be considerably enhanced. Actually, it poses a series of challenges for the coordinated development of grid and source. Therefore, it is possible to realize stochastic optimal scheduling of the large-scale wind power system when these issues in wind power precise prediction, online risk prevention and system performance improvement, active support technology advances are resolved by continuous progresses in the capability of wind power grid integration. And thus, we could expect stable operation and efficient utilization of renewable energy even when wind power is accessed in the grid on a large scale.

(W. H. Shi)

6.2 Distributed Wind Power and Microgrid System

In recent years, the wind power industry has substantially growing, and its status of market occupation would gradually shift from "supplemental energy" to "alternative energy" in the near future. However, there are still some obstacles that restrict its healthy and sustainable development such as cultivated land occupation, expensive transmission cost, and high curtailment rate. In 2016, accumulative installed grid-connected wind power capacity reached 149 million kWs, accounting for 9% of total power installed capacity, while the wind power generation is 241 TWh with annual curtailment of 49.7 billion kWh (NEA 2016). The most serious provinces were Gansu, Xinjiang, Jilin, and Inner Mongolia, which means that the abandonment rate exceeded 20%. The high proportion of wind energy curtailment can be attributed to the fact that China's onshore wind energy resources are mostly distributed in the "Three North" area. When centralized development is unable to effectively handle the issue of power transmission and local consumption, high proportion of wind power discard is inevitable.

Ever since 2010, NEA has encouraged to explore new modes of distributed wind power development that could facilitate the transformation from "scaled centralized development" to "centralized and decentralized scale development" mode. In addition, microgrid is a more advanced and flexible concept for wind power nearby utilization. It can either operate in parallel with external power grids, or supply electricity only for local loads alone. Obviously, the new mode exhibits higher power supply efficiency and reliability. In Sect. 6.2, we attempt to elucidate these new modes for readers interested in this respect.

6.2.1 Background of Distributed Wind Power and Microgrid

Distributed wind power refers to power generation technologies that use various decentralized energy sources available, including renewable energy sources (solar energy, biomass energy, wind energy, small hydropower, wave energy, etc.) and fossil fuels (mainly natural gas) that are readily available locally (Wang et al. 2016). The distributed generation system facilitates complementary utilization of multiple energy sources such as cold, heat, and electricity to meet the various energy demands of users and improves the efficiency of energy utilization. Distributed power generation can reduce the network loss and instability problems caused by long-distance transmission of electricity, and avoid the disadvantages that the development of large-scale centralized wind farms brings about by the peak-shaving capacity of the power grid, which can improve power quality and power supply reliability.

There is no clear definition on distributed wind power in China. State Grid Corporation of China's scope of application for distributed power supply in the "Opinions on Doing a Good Job in Distributed Power Grid-Connected Services" is: located near the user, the power generation can be utilized locally, grid-connected voltage level $\leq$10 kV, and the total installed capacity of a single grid-connected point does not exceed 6 MW, including solar energy, natural gas, biomass energy, wind energy, geothermal energy, ocean energy, comprehensive utilization of resources, and other types. Distributed wind power is a new type of power generation and energy comprehensive utilization with broad development prospects. The distributed wind power is the distributed wind power project which put forward a decentralized development of wind energy combined of China's national conditions, connected to grids in single-point or multi-access and centralized monitoring. Distributed wind power project refers to a wind power project that is located near the center of the power load and is not used for large-scale long-distance power transmission, and the generated power is connected to the power grid and is consumed locally. Compared with centralized wind power, the characteristics of distributed wind power development are mainly reflected in small-scale, decentralized development and proximity access, and the transmission voltage is generally three voltage levels of 110, 35, and 10 kV. In addition, since distributed wind power projects generally do not need to build new booster stations, the investment is small, and the construction period is short, so it is feasible to consider both the site selection and the economic considerations.

The distributed wind power environment is highly adaptable. Whether it is a plateau, a mountain, an island (reef), a polar or a remote area, as long as the wind energy reaches certain conditions, it can operate normally, supply power to users, and applying distributed wind power technology on off-grid power generation can effectively solve the problem of power consumption in remote areas, and it provides a new power supply mode for remote mountainous areas and extreme climate zones. The distributed wind power generation system has high safety and reliability. The power stations in the system are mutually independent. Because the users can control themselves, there will be no large-scale power outage accidents, which can make up for the lack of safety and stability of the large power grid, and continue to supply power when accident occurs. It is an important supplement to the centralized power supply system while the transmission and distribution losses are very low or even no, there is no need to build a power station, so it can reduce or avoid additional transmission and distribution costs, while the cost of civil construction and installation is low. Distributed wind power generation and solar photovoltaic power generation can complement each other. Wind turbines, solar photovoltaics, and energy storage devices can be combined into a combined power supply system through technical transformation to solve the small-scale residential electricity consumption. It also provides real-time monitoring of the quality and performance of regional power, making it ideal for powering residents in rural, pastoral, mountainous, medium, and small cities or commercial areas. The power generated by distributed wind power can be self-sufficient and consumed on the spot. It can also arouse the idle capital of the society for the development of new energy, which is in line with China's economic operation strategy of adjusting structure, expanding domestic demand and stabilizing growth.

The development of renewable energy represented by wind power is a global trend and a major policy for China to promote the energy revolution. The distributed application model is an effective solution to solve the problems of self-sufficiency, local consumption, curtailment of wind energy, which can encourage social investment, make progress in structural adjustment, internal demand expansion, and economic growth. It is also an important factor in transforming the power supply mode and power market reform. Under the situation of equal emphasis on wind power concentration and distributed development, promoting the distributed utilization of wind energy can support the realization of China's wind energy industry strategic development goals and support the use of wind energy to play a more important role in the future energy system.

Although distributed power generation has many advantages, its impact on large power grids can't be ignored. IEEE P1547 stipulates that distributed energy is connected to the grid separately. When the power system fails, the distributed energy must immediately exit the operation, which greatly limits the development of distributed energy. In order to maximize the use of distributed energy and the economic benefits it brings, as well as to improve reliability and minimize its impact on large power grids, the concept of microgrid has been proposed.

Microgrid refers to small power generation/distribution/power that is made up of distributed power sources, energy storage devices, energy conversion devices, related loads, monitoring and protection devices. The system is an autonomous system that can achieve self-control, protection, and management (Wang et al. 2014; Wang 2016). Microgrid is a concept compared with traditional large-scale power grids. The scale of large-scale power grids continues to expand, and its drawbacks are increasingly prominent. The emergence of microgrid technology has effectively overcome numerous shortcomings of large power grids. Through the realization of key technologies such as operation control and energy management, the adverse effects of intermittent distributed power supply to the distribution network are reduced. With the development of distributed energy, microgrid technology has received more and more attention. The microgrid effectively connects the power generation side and the user side, so that the user side does not have to directly face a variety of distributed power sources with different ownership and distributed access (Yang et al. 2014). The existing research and practice results show that it is an effective way to realize the performance of distributed power supply and realize the form of multiple energy sources by connecting the distributed energy to the grid in the form of microgrid and operates in parallel with the grid. It is an effective way to realize active distribution network with highly reliable supply, improved power supply reliability and power quality, it is an effective way to realize active distribution network, which can realize the transition from traditional power grid to smart grid.

The concept of microgrid was firstly proposed by the American Association of Power Reliability Technology Solutions (CERTS). The EU, the USA, Japan, and China have all carried out research on microgrid demonstration projects. According to demonstration projects, the characteristics of microgrid are mainly formulated as follows:

(1) Distributed energy in the microgrid is mainly renewable such as wind power, solar power, etc., or is based on comprehensive energy utilization, so the microgrid is "clean." These clean energy sources are greatly affected by weather conditions, so the system had better to be matched with energy storage device to meet the user-side demands for power supply quality and reliability.
(2) The microgrid is optimized for local distributed energy, adapted to local conditions, and used nearby to provide electricity or heat to nearby loads, reducing investment and loss of transmission and distribution lines and reducing costs. Compared with traditional large-scale power plants and large-scale power grid long-distance transmission, the investment cost is low, the risk is small, and the construction period is short, which is conducive to solving the power shortage problem in a short time.
(3) The microgrid is connected to the main network through a common connection point and represents as an overall controlled unit relative to the external large power grid. This type of connection requires only the technical specifications of the common connection point to meet the IEEE P1547 standard instead of all the distributed energy resources.
(4) The microgrid consists of several feeders. Depending on the importance of the load and the different requirements of the load on the quality of the power, different feeders are, respectively, connected to realize hierarchical control of load hierarchy, and the entire network is radial.

The energy storage system is a special micropower supply in the microgrid. The energy storage system consists of an energy storage unit and a bidirectional converter. When the network is running, the energy storage system can store energy. In contrast, while the island is running, the energy storage system plays an important role in speeding up the switching time, improving the power quality and balancing the inconsistency of response time between multiple power sources. Energy storage technologies can be divided into mechanical energy storage, electromagnetic energy storage, chemical energy storage, etc. (Wang et al. 2014). Mechanical energy storage mainly includes pumped energy storage, flywheel energy storage, compressed air energy storage, etc.; electromagnetic energy storage mainly includes superconducting energy storage, supercapacitor energy storage, etc.; chemical energy storage is mainly various types of storage batteries, including lead–acid batteries, nickel A battery, lithium battery, flow battery, sodium–sulfur battery, and so on. According to the external characteristics of energy storage and release, microgrid energy storage can be divided into power type and energy type. Power-type energy storage is suitable for occasions with high power demand in a short time, such as improving power quality, providing fast power support, etc.; energy storage is suitable for occasions with high energy demand, and energy storage equipment is required to provide long-term energy support. Power-type energy storage has rapid response and high power density, including supercapacitor, flywheel energy storage, superconducting energy storage, etc. Energy-type energy storage has high energy storage density, long charging and discharging time, including compressed air energy storage, sodium–sulfur battery, flow battery, lead–acid battery, lithium-ion battery, etc.

6.2.2 Present Status

1. **Worldwide status**

Distributed wind power is widely used abroad, especially in Europe and the USA. Due to its small land area and large population density, it is not suitable for the development of large-scale wind farms. It mainly adopts “small-scale, distributed, low-voltage, and local distribution” route. In the USA and European countries, basically no large-scale power supply facilities are built. It is these energy comprehensive utilization systems and distributed power sources which are attached to the user terminal market that improve energy efficiency, optimize energy structure and reduce carbon emissions while ensuring power supply. At the same time, the USA, Germany, Denmark, and other countries have formulated regulations, standards, and policies for distributed wind power to encourage and standardize the development of distributed wind power.

(1) Distributed Wind Power and Microgrid in the USA

According to the definition of the American Distributed Wind Energy Association, distributed wind power refers to the wind power devices installed in residential communities, farms, commercial office buildings, industrial areas and public facilities, and directly connected to the distribution network to meet all or part of the users themselves or nearby. The USA has studied distributed wind power generation earlier, and it leads the world in terms of technology level, equipment manufacturing, and market share. The reasons for the rapid development of distributed wind power in the USA are as follows: First, distributed wind power projects have received strong support from society. Local governments have lowered the threshold to allow residents to invest in small-scale distributed wind power projects. Second, wind power projects range from small wind turbines of tens of kilowatts to large grid-connected wind turbines of megawatts, with fixed electricity prices to meet the power needs of different types of users, including government, commercial, industrial, and residential. Third, the development process of wind farms is simple, the period from the wind farm assessment to the commercial operation is short; fourth, the distributed wind farm can directly access the grid through the local distribution network (He Guoqing 2013). Fifth, the US wind power incentives policy applies to distributed wind farms, and the federal government has tailored detailed policies for small-scale distributed wind power projects. States also have their own different policies to encourage the construction of distributed new energy projects.

Since 2010, 34 states in the USA have developed wind power in a community mode, using megawatt wind turbines to build distributed power stations. The development of community wind power has been for several years and has relatively mature operational experience. Community wind power can enjoy a 30% investment tax credit for at least 5 years. The US Rural Energy Act provides loan guarantees or allocates funds for rural wind power distributed generation projects with a cap of $500,000 or a quarter of the total project cost. At the same time, the US Department of Energy proposes that by 2020, by using the most cost-effective distributed energy system, the US electric energy production and delivery system will become the cleanest, most efficient, and most reliable in the world, which provides greater opportunities for the development of distributed wind power.

In the aspect of microgrid, the study in the USA was earlier and deeper. The concept of microgrid was first proposed by CERTS in the USA. At the same time, CERTS funded the experimental microgrid at the University of Wisconsin–Madison, and subsequently established a demonstration microgrid system in Ohio. The USA is leading the world in the research and practice of microgrid, with more than 200 microgrid demonstration projects, accounting for about 50% of the global microgrid (Navigant Research 2013). The US microgrid demonstration projects have wide geographical distribution, diverse investment entities, diverse structures, and rich application scenarios. It is mainly used to dissipate renewable distributed energy, improve power supply reliability, and provide support services for the grid as a controllable unit. From the perspective of the US power grid modernization, improving the reliability of power supply for important loads, meeting a variety of customized power quality requirements, reducing costs, and achieving intelligence will be the focus of the development of US microgrid.

In the aspects of distributed wind power policy laws and regulations, the US wind power incentive policies are suitable for distributed wind farms, and the federal government has also developed detailed policies tailored for small distributed wind power projects. There are many corresponding policies and laws in the USA. In addition to national policies, states have their own different policies to encourage the development of distributed wind power projects. The main policies include renewable portfolios standards, tax credit policy, renewable energy subsidy policy, and net electricity exchange policy. The renewable portfolio standards impose a mandatory legal requirement on the share of renewable energy generation in the USA in terms of total power generation. According to the renewable portfolios standards by the end of 2025, companies must increase the proportion of renewable energy supply to 25% of total electricity use. The tax credit policy stipulates that the grid-connected distributed wind power project can enjoy the production tax credit preferential policy of unit power generation and can also enjoy cash subsidy at one time according to 30% of the project investment amount. For off-grid or distributed wind farm, the "spontaneous use" section is not eligible for the production tax credit, but can enjoy cash subsidies. In terms of renewable energy subsidies, the US Renewable Energy Program stipulates that private and non-resident distributed wind farms in remote areas can receive government-sponsored project feasibility study subsidies, project investment subsidies, and loan guarantees. The net electricity exchange policy allows users to record excess electricity in the winter and use it in the summer. If it is not enough, it will be purchased from the grid. If there is surplus, it will be owned by the municipal government. This policy is a one-year cycle. In addition to these incentive policies, the US state governments have also set up special funds for the feasibility study of distributed wind farm projects for wind farm assessment and pre-project development.

(2) Distributed wind power and microgrid in Europe

The development of wind power in Europe mostly focuses on decentralized access. Under normal conditions, wind power can be absorbed in the local or regional power grid. In Europe, the European Commission is working on a SAVE II energy efficiency action plan that includes many different energy efficiency measures to promote the development of distributed wind power. The UK has promoted the development of distributed wind power through its Energy Efficiency Best Practices program, which has established distributed energy systems in more than 1000 farms, airports, ports, and islands, especially on farms where farmers only need to provide a piece of land to use clean electricity for free, while investors get their own benefits through electricity price subsidies.

Community wind power is an application form of distributed wind power generation that has emerged in recent years. The main purpose of community wind power generation is self-use, and excess power is incorporated into the grid and packaged for sale. European civil electricity prices are high, using social investment to solve the problem of residential electricity use and self-use, and enhance people's ideology of new energy use and energy conservation. Denmark is a pioneer in community wind power and has created many community wind power models for reference. 80% of distributed wind farms in Denmark have community wind power properties. The Danish municipal energy agency do not only buy community wind power, but also participates in investment, which plays a very important role in the popularization of community wind power in Denmark. For example, the Danish Hvide Sande Community Wind Power Demonstration Project, initiated by a group of locals, installed

Fig. 6.4 Panorama of Danish Hvide Sande Community Wind Power Demonstration Project

three 3 MW wind turbines on the beaches along the harbor. As shown in Fig. 6.5, the economic income of every 2–3 households in Hvide Sande Town relies on the project (Preben McGart et al. 2016). Large-scale offshore wind power has also affected the development of community wind power, and successfully realized offshore community wind power projects. For example, a community combined with Copenhagen Energy invested 40 MW of Middelgrunden offshore wind power project (Fig. 6.4).

Germany and Denmark are on the same page in the development of community wind power. 75% of all distributed wind power projects in Germany can be classified as community wind power. In the past decade, German community wind power has grown stronger. In Germany, the owners of community wind power can be local farmers, independent companies, and cooperatives. Independent companies generally buy shares of publicly issued by community wind power, and energy companies have more and more shares. A major feature of German community wind power is "big," and the installed capacity of some community wind power projects has gradually expanded to more than 50 MW. The Swedish community wind power has established a variety of institutional frameworks for community wind power. Dividends for members of community wind power are related to the wind power of the community they purchase and use, plus some environmental bonuses. Community wind power also saves members taxes by selling low-cost wind power directly to its members.

The experience of European community wind power development is to make community wind power successful. It is necessary for local residents to participate in community wind power projects as early as possible, and to integrate community-specific needs and conditions into the project at an early stage. Community wind farm planning is generally done by professional companies outside the community. After the project is completed, it will promote the development of local economy, bring taxes to the local government, bring cheap electricity to the residents, and provide long-term jobs, and bring positive effects.

The research and development of the European microgrid mainly considers the various requirements for satisfying the user's power quality as well as the stability and the environmental protection requirements of the entire power grid. The microgrid is considered to be an effective support for the future power grid and attaches great importance to the research on microgrid. In the "Smart Power Network" plan proposed by Europe, it is pointed out that it is necessary to make full use of distributed energy, intelligent technology, advanced power electronic technology, etc., to achieve efficient and close integration of centralized power supply and distributed power generation, and actively encourage all sectors of society to participate in the power market and promote development of power grid together. The microgrid has become an important part of Europe's future power grid due to its intelligence and diversified energy utilization. The power supply in the European interconnected grid is closer to the load zone, and it is easier to form multiple microgrids. Therefore, the research of the European microgrid places more emphasis on the interconnection problem of multiple microgrids.

European countries mainly implement incentive policies that combine compulsory repurchase, net electricity settlement, and investment subsidies for distributed wind power. The compulsory repurchase policy is widely implemented, and most of the major wind power countries in Europe adopt this policy. The net electricity settlement policy is also very effective, and this policy is used in Denmark. In addition, European countries have accordingly formulated policy-related certification standards. Market access and policy subsidies will be implemented for the units in compliance with certification standards.

2. **Domestic status**

China's distributed wind power technology mainly draws on the mature development experience of European and American countries, and the research started late. In recent years, State Grid Corporation of China, Chinese Academy of Sciences, China Electric Power Research Institute, Zhejiang Electric Power Research Institute, and Xinjiang Goldwind Sci & Tech Co., Ltd. have conducted research on distributed wind power in accordance with the current development needs of renewable energy power supply structure in China and formed some demonstration projects. But, until now, the development of distributed wind power is still relatively limited, mainly for the following reasons: Firstly, China's wind energy utilization is mainly concentrated on large-scale centralized grid-connected development mode, and there is still lack of policy support and operation mechanism for distributed utilization of wind energy. Secondly, in the "Three North Region" with good wind resources in China, if distributed wind power is developed, it still faces the problem of transmission and consumption. The southeastern region develops distributed wind power, though which can solve the problem of transmission and consumption, the distribution of wind resources needs to be seriously considered. The third is the high investment cost at earlier stage of distributed wind power project. The fourth is that distributed wind power project also requires land acquisition and strict environmental assessment procedures.

Distributed wind power is a distributed wind power project proposed in combination with China's national conditions. By the end of 2014, the National Energy Administration had approved 15 decentralized access wind power projects with an approved capacity of 762,000 kW. There are 11 projects have been connected to grid with capacity of 523,500 kW, such as the Huaneng Dingbian Wolfer Decentralized Demonstration Wind Farm with an installed capacity of 9 MW and the Inner Mongolia Damao High Waist Sea (Gaoyaohai) Wind Farm with an installed capacity of 6 MW. Decentralized utilization can achieve locally power consumption and reduce wind energy curtailment, which will become a good mode for distributed utilization of large wind power equipment.

In addition to the decentralized utilization of wind power, in order to explore the development of distributed microgrid technology and accumulate experience in the construction of distributed microgrid, during the "Twelfth Five-Year" period, China carried out preliminary technical research on the distributed utilization of wind energy and built several wind power-based, multi-energy complementary distributed microgrid demonstration projects. Wind power equipment manufacturing enterprises also actively cooperate with the development of distributed microgrid application technology, in preparation for the arrival of distributed microgrid scale application opportunities. Through demonstration project implementation, China has accumulated certain experience in large-scale microgrid system architecture design, use and management of different types of batteries, remote monitoring, fault diagnosis, remote upgrade, energy management, and micronetwork core equipment. Overall, the reliability of the microgrid system that has been designed and constructed is the main contradiction. The indicators such as economy and environmental protection are still difficult to fully estimate. In terms of microgrid planning and design technology and system operation management technology, there is a gap between China and foreign countries.

China's policy on distributed wind power was mainly proposed in the early "Twelfth Five-Year" period. Since 2011 years, the National Energy Administration has issued the "Notice on Decentralized Access to Wind Power Development" and "Guiding Opinions on Decentralized Access to Wind Power Project Development and Construction." The definition of decentralized access wind power projects, access voltage levels, project scale, examination and approval, engineering construction, and acceptance have been strictly defined, clearly indicating the state's attitude to encourage decentralized development of wind power. As the wind industry vane, the notice "To do a good job in wind power integration and consumption in 2014" proposed to vigorously promote the development and construction of distributed wind resources. In 2013, State Grid Corporation of China issued the "Opinions on Doing a Good Job of Distributed Power Grid-Connected Services," which proposed a standard for the new energy distributed energy that is allowed to be connected to the grid, and promised to provide convenient facilities for distributed energy projects to access the grid. "The Interim Measures for the Management of Distributed Generation," issued by the National Development and Reform Commission, brings up that the construction and operation of the user at the site or near the user, with the user-side self-use in main, the excess power upload the grid. There are also rules on power generation facilities of distribution network system which is characterized by balancing adjustment, and energy integrated cascades utilization of multi-generation facilities with power output of management. Construction fund subsidies or unit power generation subsidies are provided for eligible distributed generation. Although the Chinese government and related agencies have issued some policies on distributed generation, the overall development of distributed wind power projects in China has lagged behind, and there are few technologies and experiences to draw on. State Grid Corporation of China has formulated the "Technical Regulations for Distributed Wind

Power Access to Grids," which has made provisions for grid-connected technologies, but the relevant standards system still needs to be improved. Therefore, it is necessary to establish and improve corresponding policies, standards, and systems in light of the actual needs of China's development to accelerate the development of distributed applications of wind energy.

6.2.3 Market Demand Analysis

Among many renewable energy sources, wind power generation is one of the most widely used and most mature technical conditions. With the development of distributed generation and microgrid technology, renewable energy such as wind energy is an inevitable trend to be used as distributed power generation. China's wind energy resources are widely distributed. Many areas such as mountains, islands, and remote pastoral areas have excellent conditions for constructing distributed wind farms. Distributed wind power generation technology has broad application prospects and commercial potential in China.

At present, China's distributed wind power generation is mainly small and medium-sized wind turbines. Several microgrid power generation demonstration projects based on small- and medium-sized wind turbines have been built, such as small wind turbines that supply power to farmers and herdsmen in remote mountainous areas. Today, in promoting energy conservation and emission reduction and developing a low-carbon economy, some cities and industrial parks are gradually developing and utilizing new energy sources. Wind power generation technologies are continuously applied to urban construction for its safety environmental protection, mature technology, and environmentally friendly, such as the distributed intelligent microgrid demonstration project of the large-scale wind turbines designed by Xinjiang Goldwind Sci & Tech Co., Ltd.—the distributed microgrid demonstration project of Jiangsu Dafeng Commercial Park (Hesheng 2016), as shown in Fig. 6.5. With the depletion of traditional conventional energy sources, the advantages of wind power will become more prominent. The advancement of science and technology and

Fig. 6.5 Panorama of distributed microgrid demonstration project in Jiangsu Dafeng commercial district

the further improvement of the social and economic level will increase the demand for electricity, and the application of distributed wind power will increase in the future. To develop distributed wind power and microgrid has the following benefits:

1. The development of distributed wind power and microgrid technology is an important way to alleviate the contradiction between supply and demand of wind power and solve the problem of wind energy curtailment. In recent years, China's installed wind capacity has grown rapidly, especially in areas with abundant wind resources as "Three North," but the problem of wind energy curtailment is more serious. Significant progress has been made in large-scale wind power equipment and its key technologies for grid connection. However, due to the limitation of grid transmission capacity, local power that cannot be absorbed cannot be timely delivered to the mid-eastern and south load centers, resulting in huge waste of resources. The development of distributed wind power and microgrid technology, which can combine with local resources and load conditions adjusting measures to local conditions and achieve flexible development and local consumption, is an important way to alleviate the current contradiction between supply and demand of wind power and solve the problem of wind energy curtailment.
2. The development of distributed wind power and microgrid technology is an effective means to improve wind energy utilization efficiency and reduce costs. Large-scale centralized wind farms have high requirements for resources and site selection. In recent years, areas with excellent land-based wind resources have been fully developed, while regions with relatively poor wind resources are not suitable for large-scale centralized wind power development. In these areas, the distributed wind power development model can be used to solve the problem of local electricity consumption while avoiding large-scale wind power transmission over long distances. Compared with the construction of large-scale wind farms in remote areas and large power consumption in long-distance transportation, distributed wind power systems are arranged in small-scale and decentralized manners near users, with advantages such as local consumption, local use, nearby access and no need long-distance transportation, which reduce the cost of wind power development.
3. The development of distributed wind power and microgrid technology will strongly promote the utilization of renewable energy in the central and eastern regions of China. "The 13th Five-Year Plan for Renewable Energy Development" has proposed to optimize the wind power development and distribution, and to shift the core of wind power development and distribution from "Three North" to the mid-eastern China. The "Thirteenth Five-Year Plan for Wind Power Development" clearly stated "Improving the level of wind power development and utilization in the mid-eastern and south regions," and using the mid-eastern and south regions as an important incremental market for the continuous development of wind power during the "13th Five-Year" period and proposes the target that increasing installed capacity of the grid with a capacity of more than 42 GW of new onshore wind power in the mid-eastern and south regions by 2020. Considering the conditions of wind resource, topography, and land in some areas of

mid-eastern China, it is appropriate to cooperate with the development of distributed wind power construction in accordance with the principle of "adapting to local conditions and accessing nearby" to ensure the realization of the target.

4. The development of distributed wind power and microgrid technology will effectively solve the power problem in remote or island areas. There are nearly 500 islands with residents in China, in which there are still about 50 islands without electricity supply. In the islands with electricity supply, the proportion of electricity from the mainland is 65%, and that of thermal power is 13%. For the island without electricity which is far away from the mainland, the traditional mode power supply has certain pollution, while the power supply from the land grid has the problems of high cost and difficult construction. The development of distributed wind power and microgrid technology can effectively solve the problem of power consumption in remote or island areas, and there are some demonstration applications in China, such as the Zhoushan East Fushan Island Wind/PV/Storage/Diesel microgrid power generation system under the supervision of Zhejiang Electric Power Research Institute. The power grid belongs to the island power generation system. It uses renewable clean energy as the main power source and diesel power generation as the auxiliary power supply mode. It supplies power for the island's residential load and a set of 50 tons of desalination system.
5. The development of distributed wind power and microgrid technology will fully mobilize the enthusiasm of all parties involved in the development and utilization of renewable energy. Large-scale centralized wind power projects participators are mostly large power generation groups, central energy enterprises, etc. Distributed wind power is relatively small in scale compared to centralized wind power, and the construction period is short. The development of distributed wind power and microgrid technology encourages the participation of central energy enterprises. At the same time, it will fully mobilize the enthusiasm of local state-owned, private, foreign-funded enterprises, and even electric consumers to participate in the development and utilization of renewable energy, and break the veto power of grid enterprises to access distributed energy, and form a pattern of participation in the development of distributed energy.
6. The development of distributed wind power and microgrid technology will provide strong support for China to explore regional energy system architecture based on renewable energy. Renewable energy has become a major strategic move for global energy transition and achieving the goal of addressing climate change. The basic trend of global energy transition is to realize the transformation of fossil energy system into low-carbon energy system, and finally enter the age of sustainable energy based on renewable energy. The future development path of energy will be from the current fossil energy as main energy plus large-scale use of renewable energy, to the fossil energy need to fit high-scale application of renewable energy, and finally to the era of renewable energy that renewable energy as the main source. Vigorously developing distributed wind power and microgrid technology will establish a new power industry system that distributed power supply and centralized power supply, microgrid and the large power grid

complements and supports each other, which can improve the efficiency of power systems, reliability, and safety of power supply, and provide strong support for China to explore regional energy system architecture based on renewable energy.

6.2.4 Technical Route and Trends

1. **Technical route**

During the "Thirteenth Five-Year Plan" period, the new installed capacity and growth rate of renewable energy will far exceed the traditional fossil energy, and distributed wind power will be greatly developed. The main technical routes are as follows:

(1) Research on wind resource assessment technology for distributed wind power development

Research on distributed wind power resource assessment based on virtual wind tower, optimized siting of wind turbines and selection of access points will be carried out. The theoretical methods for the observation of distributed wind turbines in high altitude, high temperature, sandstorm, typhoon, thunderstorm, snow frost and other wind characteristics and models, and basic data of complex terrain mesoscale numerical models will be studied to provide theoretical data for wind turbine design in China. Research on high-precision high-resolution wind field numerical simulation technology based on mesoscale meteorological model and remote wind tower will be carried out. Study the model calibration method based on measured data to improve the accuracy of numerical simulation results and provide reliable virtual wind tower parameters for distributed wind power assessment. Study the influence of complex underlying surface environment on wind energy resources, fan safety, and key parameters of operation, and study the distributed wind power optimization location method.

(2) Research on environmental impact of distributed wind power

At present, the noise of wind turbines in China is about 70–90 dB. The installation site of distributed wind turbines is different from that of centralized wind turbines. If distributed wind turbines are installed near residential areas, noise problems will be difficult to avoid. In particular, wind power has obvious anti-peak characteristics. In the middle of the night, wind turbine operation will directly affect the rest of people near the installation site. Europe clearly stipulates that the installation site of distributed wind turbines should be one kilometer away from residential areas. Although the development of distributed wind power in China has just started, how to solve environmental problems such as noise disturbances should be considered in terms of technical aspects and policies.

(3) Research on wind turbines and key components for distributed wind energy

In view of the actual situation of low-wind-speed zones in most parts of China and the needs of applications of distributed wind power, domestic enterprises have developed targeted wind turbine products and solutions through technological innovation. The most obvious feature is that the rotor blades are longer and the towers are higher, which can capture more wind energy resources. Taking a 1.5 MW wind turbine as an example, among the units installed and put into operation in China in 2014 and 2015, 1.5 MW units with a diameter of 93 m and above accounted for the majority. In the past three years, 2 MW units with a diameter of 100–121 m have come out one after another and have become mainstream models. These low-speed wind turbines will play a better role in the distributed wind farms in the provinces of southern China, but the wind energy capture and control stability at low wind speeds need to be further improved. The research and development of low-speed wind turbines needs to be focused on solving problems such as refinement and high efficiency, thus supporting the overall improvement of distributed wind power technology.

(4) Research on accurate prediction technology of distributed energy and demand side response

The distributed power points are wide-ranging; the project scale is small, the time, location, and capacity of the project are arbitrarily large. The distributed power supply is connected in a large scale, making the power demand and distribution of the corresponding distribution network layout difficult to predict, increasing the randomness, especially for wind power which has great intermittent and random nature. The distributed wind farm is different from the centralized grid-connected wind farm. It is necessary to configure the wind power prediction system according to the specific characteristics of the wind farm scale, the site, and the operation needs of the grid. The power prediction system can be configured on a single distributed wind farm side, or can be centrally configured on multiple distributed wind farms. The current power prediction system has low prediction accuracy, so it is necessary to develop accurate prediction technology of distributed wind power and demand side response to optimize grid dispatching and power grid planning, improve grid safety and reliability, and enhance the competitiveness of wind power generation.

(5) Research on interconnection technology between distributed wind power and microgrid, interconnection technology of different microgrids

Technically, according to the needs of islands, remote areas, urban distributed power generation, etc., we need to develop large-scale distributed power generation technology, build an active distribution network, and monitor the load and distributed resources operation of main network, distribution network and user side in real time. The strategy of optimized coordinated control is proposed. On this basis, the interconnection technology of different microgrids will be further developed. Microgrids interconnection does not only enable energy sharing between networks, improve the utilization of renewable energy, but also improves the power supply security and reliability of the load within the network. Microgrids interconnection puts forward higher requirements for system planning and design, energy management and equipment functions. Each part must not only be able to form a network independently, but also be able to interconnect and form a large micronetwork with plug-and-play functions system. Through the implementation of microgrids interconnection design integration technology, microgrid interconnection operation control and energy management technology, to realize the access of a large number of distributed energy.

(6) Research on multi-energy complement technology of distributed wind power and other renewable energy sources

In terms of distributed utilization, wind and solar energy complement each other. The wind–solar hybrid power generation system compensates for the shortcomings of the wind power and photovoltaic independent systems in terms of resources. The wind–solar supply is an ideal independent power supply with higher reliability and more reasonable cost. China has insufficient research on wind and solar energy complementary utilization, and complementary use of wind and solar resources has not played a great role. Therefore, it is necessary to study the wind–solar complementary system and the coordination law to take advantage of the complementary use of wind and solar energy in distributed utilization.

2. **Key development orientation**

In terms of distributed wind energy utilization, the overall layout will be carried out in basic theoretical research, high-tech research and innovation, demonstration application, and industrialization promotion. The development path of distributed wind power industrialization is shown in Fig. 6.6. The key development directions are as follows:

(1) From 2016 to 2020, tackling and research of basic theory, common technical issues will be carried out in aspects of distributed wind turbines and blades, electrical control systems and other key components, distributed wind farm wind energy resources assessment, microsite selection, design and distributed wind energy utilization, and other renewable energy complementary use. For distributed wind turbine design, generators, converters, and other key components, research will be carried out in complementary integrated utilization between distributed wind energy and other renewable energy. In the development of large wind turbines, the role of small- and medium-sized wind turbines in distributed utilization should be considered.
(2) In 2020–2030, we will further promote the demonstration applications and industrialization of efficient, low-cost, reliable, and safe distributed wind energy utilization systems and key equipment. In terms of distributed wind turbines and its key components, distributed wind farm development, we will further enhance the independent innovation, research, and development, accelerate the multi-energy complement of renewable energy and microgrid demonstration application projects in the complementary utilization of distributed wind energy utilization and other renewable energy sources, and combine distributed wind

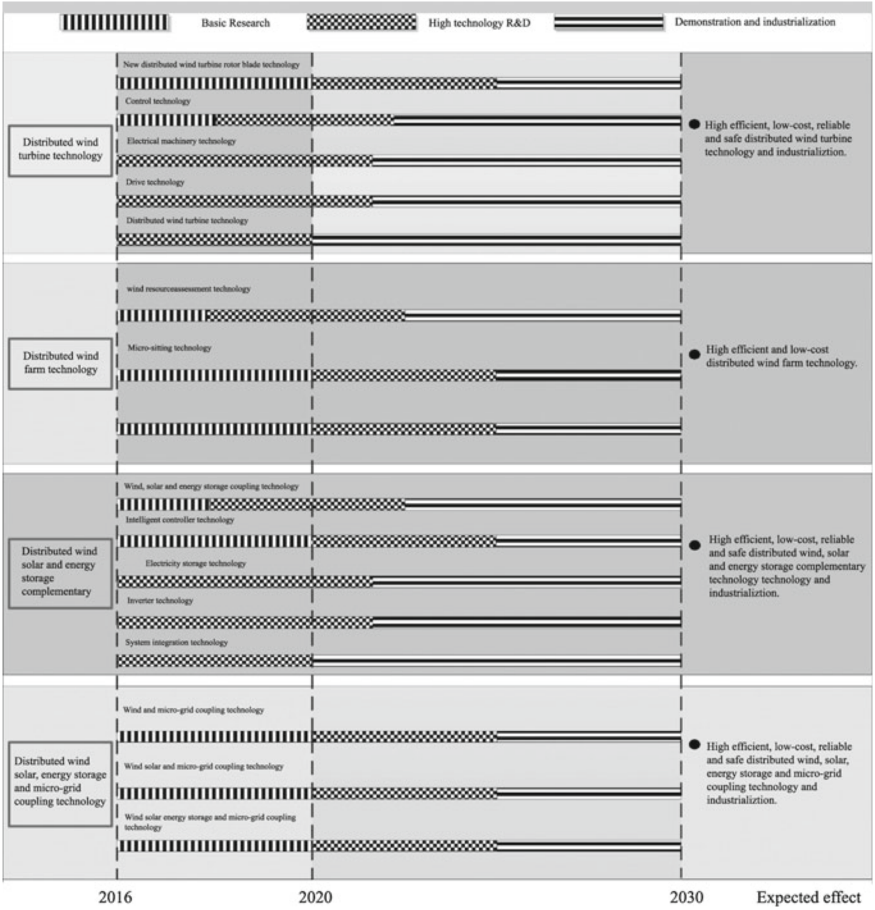

Fig. 6.6 Development route of distributed wind power and microgrid (Qi Hesheng 2016)

energy utilization with Internet technology such as Internet of things, cloud computation, big data, etc. Sum up advanced experience and models to promote the scaled development of distributed wind energy utilization.

6.2.5 Concluding Remarks

The development of distributed wind power and microgrid technology is an important direction to alleviate the contradiction between supply and demand of wind power and solve the problem of wind energy curtailment. It is an effective mean to improve the efficiency of wind power utilization and reduce costs and will remarkably promote the utilization of renewable energy in the central and eastern regions of China. It will effectively solve the problem of power consumption in remote/island areas, and at the same time fully mobilize the enthusiasm of all sectors of society to participate in the development and utilization of renewable energy, and provide strong support for China to explore regional energy system architecture based on renewable energy.

The main technical routes of distributed wind power and microgrid are: wind resource prediction technology, environmental impact estimation technology, manufacture technology of wind turbines and components, distributed wind power integration technology, accurate wind power forecast technology, technology of demand-side response prediction, interconnection technology between distributed wind power and microgrid and multi-energy complement technologies in distributed wind power and other renewable energy. The key development directions of distributed wind power and microgrid are: industrialization of distributed wind power and farm technology with high efficiency, low cost, high reliability, safety; industrialization of distributed wind–solar–storage complementary technology with high efficiency, low cost, high reliability and safety; the industrialization of distributed wind–solar–storage intelligent microgrid coupling technology with high efficiency, low cost, high reliability, and safety.

(H. H. Xu, S. J. Hu)

6.3 IT-Based Intelligent Wind Farm

“Internet +” is essentially a fusion of resources. It is a kind of “power” that promotes the success of various sectors through integration. It is a kind of “path” of industrialization to success on the basis of integration. It is the “locomotive” for economic and social development via integration (Zhou 2015). Wind energy is increasingly drawing people’s attention and being favored due to its clean and renewable features. The energy Internet closely related to the wind energy industry then becomes hot topic of practitioners in the community of wind power industry.

In the era of “Internet +” and “cloud platform,” cloud platform-based wind farm microsite selection, data platform-based wind turbine selection, and O&M (operation and maintenance) have also frequently entered people’s sight. Some of the unsolvable problems in traditional wind power systems have become routine affairs in the Internet age.

As for intelligent wind farm based on Internet technology, the information and intelligent platform for wind farm operation is constructed, and the unit nodes of wind turbine, background monitoring, operation, and maintenance are connected, enabling the wind farm “think” and “manage” by itself. Intelligent wind farm includes smart wind farm and smart wind turbine. Smart wind farm is embodied in smart microsite selection, smart wind farm resource management, and O&M, as well as smart energy network integration. It is mainly represented by implementing precise microsite selection, which is based on mesoscale and big data wind resource network, and adopts physical modeling technology using satellite and remote sensing; wind farm and wind turbine resource management based on big data, and wind turbine life cycle data management using intelligent monitoring system; wind farm power forecasting and smart energy management platform based on multi-resource integration and self-optimization. Smart wind turbine is embodied in intelligent power generation control, intelligent adaptive control, and intelligent operation control. The wind turbine can intelligently control the yaw according to wind direction prediction and wind power prediction information, provide differentiated memory configuration for complex terrain areas, and realize optimal energy capture for wind turbines under different environments and low-wind-speed circumstances based on air density and ambient temperature; and in terms of O&M, achieve status assessment, intelligent fault warning and diagnosis, and real-time intelligent routine inspection solution.

6.3.1 IT in Wind Power Prediction System

According to recently announced report on wind power integrated operation in 2016 by NEA, China's wind power generation was 241 TWh with the curtailment of wind energy of 49.7 TWh.

The fluctuation of wind power and the characteristics of counter-regulation peak are the important factors that affect final consumption capacity of wind power on power grid, but the more immediate reason is the randomness of wind power, which is depending on the stabilization ability of traditional energy sources. When the adjustment ability reaches the limit due to reasons such as energy resource structure and cost, wind power supply must be so coordinated to ensure the stability of power system. Fundamental reduction of random fluctuation of wind power could significantly upgrade the ability of power grid for wind power consumption. High-precision wind power prediction system can foresee wind power output ahead of 4 h or even 96 h in the future by little cost, which can directly reduce the randomness of wind power and the demand for peak regulation capacity on the power grid so as to mitigate the problem of wind restriction to a certain extent.

The Internet technology has been used in the research and development of large-scale wind power prediction system in China, but the early wind farm prediction system directly forecasts the short-term and ultra-short term at the wind farm after obtaining the cloud numerical weather prediction (NWP) data from the Internet. Since the prediction accuracy is relying on the NWP data source, the selection of prediction model, and parameters setting, there is no general optimal model suitable for all kinds of wind farm, thus resulting in low accuracy of the short-term prediction. To improve such circumstances, it is necessary to make use of the Internet technology to interact and cooperate with the wind farm forecast system by adding centralized prediction servers on the cloud. Figure 6.7 illustrates a schematic diagram of the new energy power prediction system.

The wind power prediction system is a distributed system based on the Internet, including NWP, prediction server in wind power prediction manufacturer center,

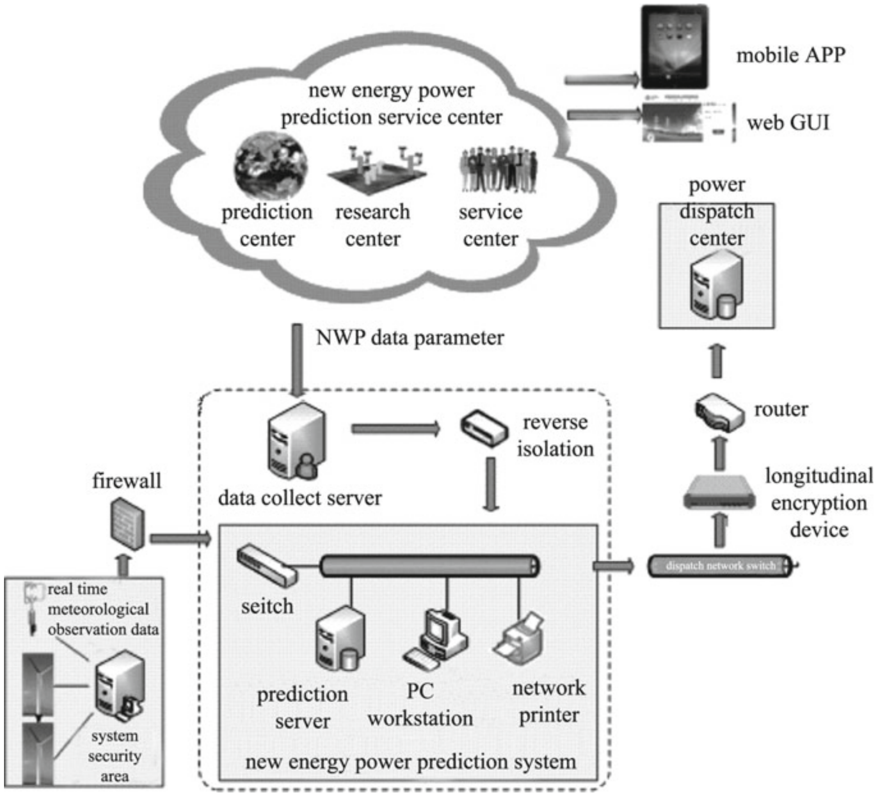

Fig. 6.7 Energy power prediction system

wind farm end prediction server, dispatching prediction master station, Web publishing server, wind metering tower, etc. In the whole process of realizing the function, Internet technology is indispensable. NWP is the key input source for short- and ultra-short-term prediction and is released by professional meteorological departments and companies through the Internet. The centralized prediction server obtains NWP data through the Internet and sends it to the end prediction system of wind farm.

At wind farm side, the prediction system can request the NWP data from cloud through the reverse isolation device. In the wind farm side local network, the prediction system and the wind farm SCADA system, the wind tower equipment, and the boost integrated automation system usually carry out the data exchange using the TCP network protocol. The ultra-short-term prediction results of wind farm side and the short-term prediction results from the external network center server need to be uploaded through the network to the dispatching wind power forecast master station. In some wind farms, the external network Web server is also configured to publish the results to the network, and users can use the browser to access the Web prediction results on the Internet. At the central server side of the prediction system manufacturer, the technical personnel can run multiple sets of prediction algorithms at the same time, adjust the specific models, algorithms, NWP data sources, input parameters, select the optimal short-term prediction results, and pass to the wind farm through the network. At the same time, according to the wind farm operation data uploaded regularly, the short-term prediction model will be corrected from the feedback. As the network technology is widely used in the whole system, the data interaction becomes complicated, including the network cloud to cloud, cloud to wind farm, and the data transfer among different security partitions within the wind farm. Therefore, for the sake of network security, it is essential to ensure system network security by reasonably increase the corresponding forward isolation, reverse isolation, VPN, and such devices according to the actual data flow.

6.3.2 IT in Wind Farm Maintenance System

Wind farm operation and maintenance is an indispensable guarantee to ensure the reliability of wind turbines, improve the operating efficiency of wind farms, reduce the cost of wind power, and improve the investment benefit of wind farms. The traditional O&M method is to set up a professional O&M team for regional operation. However, its main drawbacks are:

- In general, wind farms are scatteredly located in remote areas, making it difficult for centralized management of O&M personnel and spare parts warehouses;
- The current O&M is mainly focused on emergency O&M and regular routine inspection, thus the failures can't be troubleshot and handled in time, nor the best inspection plan be formulated, thus leading to the decrease of the wind turbine available, and the increase in O&M costs;
- The lack of means of equipment condition monitoring (such as vibration monitoring system, etc.), and analysis of real-time operation data of wind turbines, tends to cause long-term "sub-health" operating condition;
- The historical operation data of wind turbines is insufficiently stored and cannot be utilized by data mining technology;
- Reasonable sharing is not effective in the wind power industry nor the collaboration to solve the common equipment failures.

In order to change the situation mentioned above, it is necessary to employ the Internet technology to institutionalize, standardize, and intelligentize the wind farm O&M to further enhance the benefits on the basis of current standard.

Adopting the Internet model and big data analysis method, applying cloud computing to the wind farm O&M, establishing a smart cloud maintenance platform exclusively for wind farms, and combining the Internet technology to connect the whole life cycle process of wind turbine operation in series, it is expected to achieve the wind farm intelligent O&M, the reduction of personnel on duty, or even unattended mode.

Combined with the wind farm cloud O&M platform, it is able to realize multi-layer, multi-terminal, and all-round intelligent wind turbine monitoring and early warning functions, as well as whole life cycle wind turbine information management and intelligent wind turbine online monitoring system. On the basis of digitization, centralization, and remoteization of wind farms, all aspects of wind farm management will be linked. Centralized monitoring, fault warning, work order distribution, and spare parts allocation can be realized within the digitized platform, hence more effective O&M and improvement of wind farm resource management and O&M efficiency. In the meantime, based on the massive data of wind turbine operation and the O&M experience of wind farm personnel, the data generated during each process of O&M can be continuously mined, explored, and integrated, thus significantly reducing the response time, the mean time to repair, and the overall O&M costs. Based on the big data "smart operation and maintenance," the wind farm can be transformed from "fault O&M" to "planned O&M," stepping toward the goal of fault-free wind turbine operation.

1. **Composition of Wind Farm Intelligent O&M Cloud Platform**

Figure 6.8 shows the block diagram of the intelligent O&M cloud platform of the wind farm. Except for the conventional monitoring of the power parameters, wind parameters, and wind turbine operation status, the wind farm intelligent O&M cloud platform also performs vibration fault warning and diagnosis on the operating states of main shaft, gear box, generator, blade, and other important components. At the same time, independent information exchange can be carried out between the various systems within the platform, making appropriate adjustments according to different

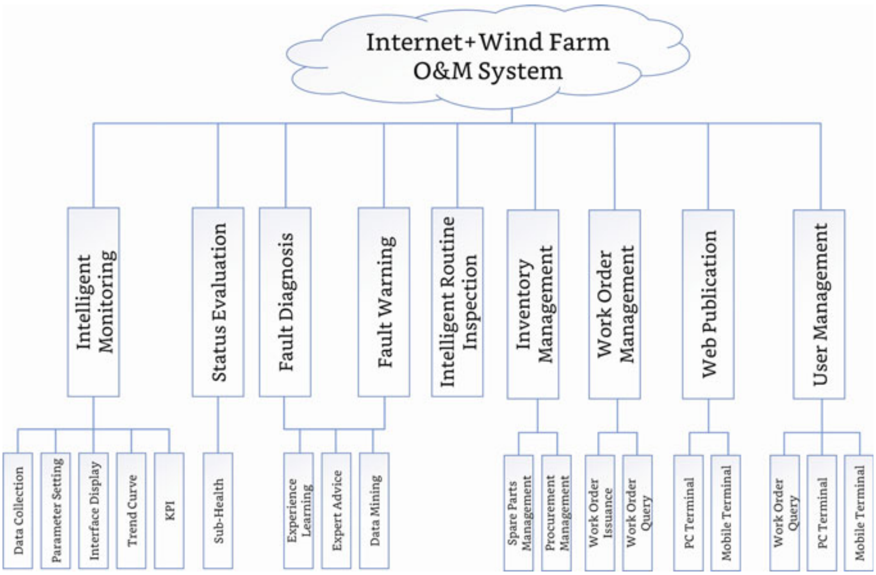

Fig. 6.8 Block diagram of wind farm intelligent O&M cloud platform

operating and wind power conditions. The wind farm intelligent O&M cloud platform includes nine subsystems: intelligent monitoring, status evaluation, fault diagnosis, fault prediction, intelligent routine inspection, inventory management, work order management, Web publication, and user management (Mao et al. 2016).

The wind farm intelligent O&M cloud platform helps users solve the remote access, secure data sharing and O&M issues of wind power generation equipment and systems. Users can share system data, get informed of operation status, and operate the system on-site via remote access, all through the Internet using mobile devices such as ordinary PC and mobile phone. In the meantime, the wind farm intelligent O&M cloud platform applies data mining technology and intelligent algorithms to conduct fault warning and diagnosis and generates equipment maintenance or repair plans automatically. The intelligent O&M cloud platform regards the wind turbines established in different wind farms as the main monitoring target to implement functions such as data acquisition, equipment control, parameter adjustment, fault warning and diagnosis, maintenance and repair planning and wind farm status assessment. The intelligent O&M cloud platform is divided into three parts, as shown in Fig. 6.9 (Wang 2016).

(1) On-site monitoring part: It is mainly composed of sensors distributed in various parts of the wind turbine, communication subsystems in the wind turbine control cabinet, and on-site monitoring servers. The communication subsystem consists of data acquisition module and real-time controller, performing anti-interference filtering and A/D conversion on the sensor acquired signals. The on-site monitoring server receives the uploaded data and stores it in the database.

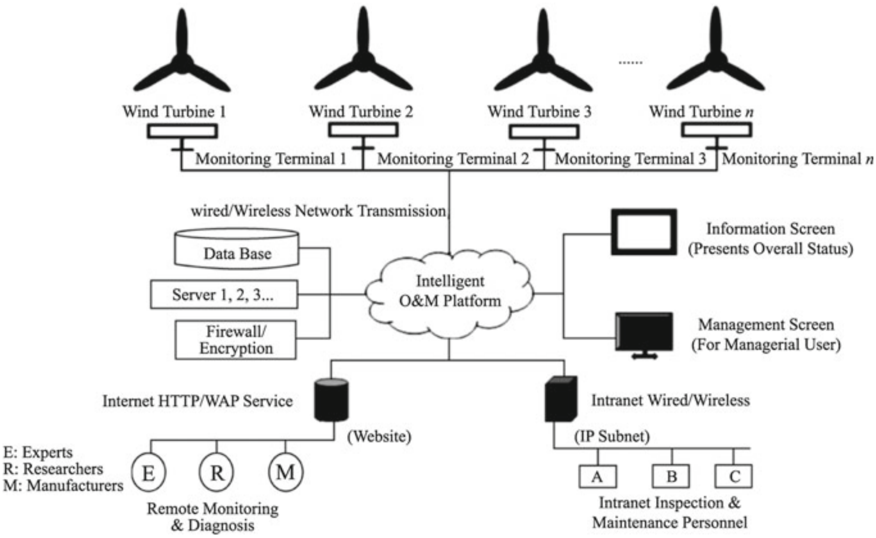

Fig. 6.9 Hardware architecture diagram of the intelligent O&M cloud platform

The data analysis module analyzes and organizes the data and transmits it to the intelligent O&M cloud platform through wired or wireless network.

(2) The cloud platform core part: The hardware mainly includes servers, switches, storage devices, firewalls, and encryption devices, and servers involve Web servers, communication servers, application servers, database servers, and management servers. The cloud platform performs algorithm processing, data mining, Web publication on the data, as well as isolation, multiple backup, and encrypted storage in order to ensure data security. At the same time, the network is under isolation, intrusion detection, and network-wide monitoring. Management personnel can log into the cloud platform servers to conduct managing operation.

(3) Cloud data sharing part: On the one hand, inspection personnel can refer to the monitoring data, maintenance suggestions, and inspection plan provided by the intelligent O&M cloud platform through the internal network, helping wind farms receive the most efficient maintenance and repair; on the other hand, advices can be given by experts, researchers, and wind turbine manufacturers at home and abroad using the monitoring data, serving as references for inspection personnel. Manufacturers can make rational improvement to wind turbines based on operation status to enhance their performance and reliability.

2. **Functions of Wind Farm Intelligent O&M**

(1) Intelligent Monitoring

Based on the large-scale wind turbine Internet of things (IoT) system, various types of on-site sensors, including wind speed, wind direction, drive train vibration, rotation speed, angle, displacement, temperature, etc., are used to collect data of diverse monitoring signals in real time.

Real-time sensing of changes in various physical quantities based on different types of sensors; standard data collection and protocol conversion through PLC system; data pre-processing, data updating, and creation of supervisory control and data acquisition system (SCADA) or condition monitoring system (CMS) database; data transmission to the big data center through the Internet; finally, data display, curve analysis, statistics, fault diagnosis, fault warning, data sharing, and other functions. Nowadays, all wind turbine manufacturers at home and abroad have developed their own SCADA or CMS.

Monitoring data from SCADA or CMS on-site are filtered and analyzed multi-dimensionally. Based on the theory of modern control technology, the farm-level control decision algorithms for wind farm clusters are developed, such as wind farm cluster wake control strategy, whole-farm optimal Kopt tracking, and wind farm cluster power optimization control. These advanced farm-level control algorithms can be used for wind farm cluster operation control decisions to achieve a significant increase in wind farm cluster power generation.

Based on the intelligent O&M cloud platform, a set of evaluation index system is designed, covering four aspects: power generation performance, availability, reliability, and economy of operation and maintenance. The index system integrates the latest four categories of KPI indicators in the wind power industry at home and abroad, and combines the four categories of indicators with the wind turbine operating quality system. By layers of drilling of the indicators, the shortcomings of wind turbine operating quality or wind farm operation could be discovered. Through technical and managerial improvements, increase of wind farm power generation can be achieved.

Through analysis of KPI indicators by the layers of drilling, the power loss is continuously broken down and displayed. It is designed with a specific quantitative analysis of the power generation performance for power loss due to wind turbine performance; it is designed to have a quantitative analysis of the availability for power loss due to failure, then classify the power loss by component/wind turbine/time, and finally, narrow down to the power loss caused by each fault stop; it is designed with special indicators to quantitatively analyze the power loss caused by human factors, such as power loss due to fault-free maintenance; it is designed with special indicators to quantitatively analyze the power loss caused by grid factors, such as power loss due to grid failure, operator shutdown power loss, non-stop power limit, etc. It is designed to have a quantitative analysis of power loss caused by environmental reasons, such as low temperature, high temperature, low-wind-speed standby, high-wind-speed standby, and yaw untwisting shutdown. After finding the causes of power loss, corresponding measures can be taken to make improvement and prevention, thus increasing the power generation.

(2) Status Evaluation

There are three states of wind turbines: normal operation, fault stop, and “sub-health” operation. In the normal operation state, the wind turbine is under normal power generating condition, and each component works properly; in the fault stop state, the wind turbine reports fault stop or other damage; in the “sub-health” operation state, the wind turbine is under power generating condition, but individual components are on the verge of fault, tend to suffer from damage, or cause the wind turbine to stop when no fault reported. When the wind turbine is in sub-health state, although the wind turbine has no fault or maintenance demand, its overall power generation performance, life span, and reliability show gradually decreasing trend over time. The occurrence of fault state is not instantaneous, and the transition from normal state to fault state is an accumulated process (such as gearbox bearing wear). However, if the fault state could be predicted in advance and timely adjustment could be made, it will be especially important for guaranteeing the enduring operation of wind turbine and optimizing the economy of O&M. Therefore, assessing the current state of the wind turbine, the sub-health state in particular, and implementing preventive maintenance are of great significance for stabilizing the wind turbine power generation and ensuring its life span. Figure 6.10 shows the distribution of power losses of a wind farm in northwest China from 2012 to 2015. From the figure, we can find that the power loss caused by power generation performance accounts for 2–3% of power generation. With the goal of power loss reduction, evaluating the current state of each component of the wind turbine, implementing preventive maintenance plan based on

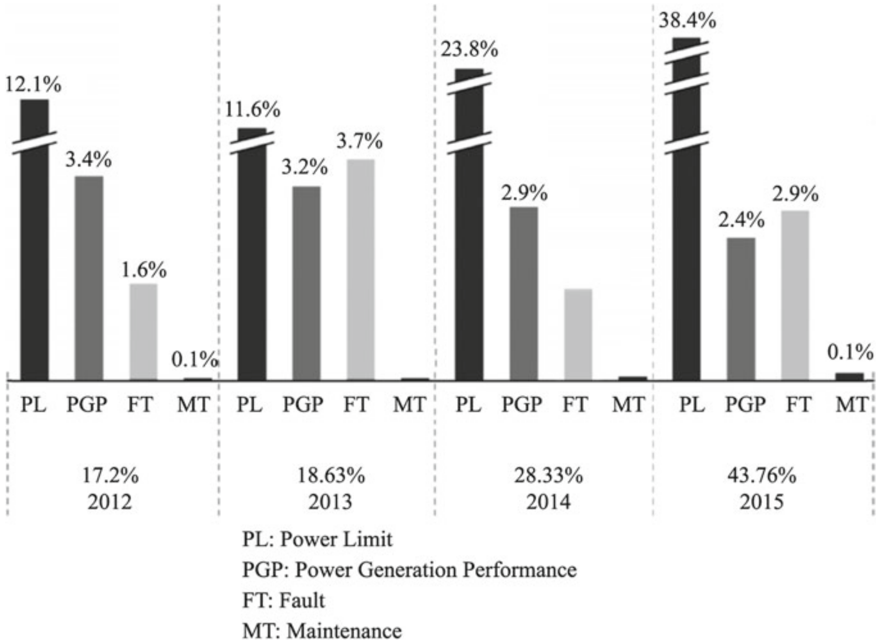

Fig. 6.10 Distribution of power loss of a wind farm in Northwest China from 2012 to 2015

the evaluation results, and arranging maintenance activities considering the weather, restrictions, etc., it is able to minimize the power loss and reduce O&M costs.

The sub-health state of the wind turbine is a state when the wind turbine gradually changes the normal response mechanism under the action of fatigue load, causing cumulative damage and accelerating the process toward failure. Wind turbines operate in complex environments, leading to both periodic and random loads. The periodicity comes from the rotor rotation effect, while the randomness mainly roots in the wind loads and other occasional loads, such as typhoon, earthquake, start loads, and stop loads. Wind turbines are typical systems that bear high cyclical fatigue loads, with an equivalent cyclical fatigue load of up to 107 cycles over a 20-year design life.

The "sub-health" status evaluation methods are mainly categorized into empirical method and data-based method.

1) Evaluation resulting from the experience of the monitored site personnel and technical experts. By using the wind farm intelligent O&M cloud platform's monitoring function, the operation and maintenance personnel and technical experts can analyze the changes of component parameter values through monitoring data, and give judgements about the state of wind turbine components.
2) Evaluation resulting from the experience accumulated by the operation and maintenance personnel doing regular inspection work.

3) Evaluation based on the wind turbine KPI index threshold computation. For electrical components, threshold method, comparison method, gradient method, and correlation analysis method are employed to analyze the wind turbine operation data.
4) Evaluation based on wind turbine machine learning, feature extraction, and data mining.

For mechanical components, based on the wind turbine operation data, quality ensured, collected by SCADA or CMS system, as well as the accumulated large amount of mechanical damage cases and their data, applying machine learning methods to conduct data analysis, data mining and modeling, and establishing a long-term "physical examination" mechanism for the wind turbine by looping the data analysis process, it is able to discover potential risks in real time.

The wind turbine component status evaluation results are displayed in real time on the intelligent O&M cloud platform. When components are in the sub-health state, through Web publication, the O&M personnel on-site can make inspection plans according to the current situation, selecting either a low-wind-speed stop period or a power-limiting period, to avoid power loss. At the same time, after the establishment of wind turbine component sub-health model, analysts can apply the model to find out the historical sub-health time cycle and frequency, as a consequence, they are able to aggregate the sub-health status time since the beginning of the wind turbine operation, assess the reliability level of the components, and employ the time series method to predict the life span of wind turbines.

(3) Fault Diagnosis and Early Warning

Using the artificial intelligence technology, it is able to realize the fault diagnosis of wind turbines, while releasing the warning notice through the intelligent O&M cloud platform, it is able to realize the fault prognosis and preventive maintenance. Fault diagnosis methods building on artificial intelligence research includes fault tree analysis, fault type and impact analysis, artificial neural network, expert system, etc. The fault trees are applied to conduct qualitative and quantitative analysis of mechanical components, which provides maintenance guidance for the personnel after the fault occurs and the work order is issued, helping them accurately find the fault location. This method can analyze the system fault both qualitatively and quantitatively. It represents the cause of system fault and the fault mode through tree-shaped logic diagram, with clear hierarchy and visible fault relationship. Combined with the fault probability, it is able to determine the influence degree of the cause of fault via quantitative importance analysis, thus optimizing the system design (Guo 2012).

Figure 6.11 shows the technology roadmap of the fault remote diagnosis system for general mechanical components. Relying on the intelligent O&M platform, mechanical components can be diagnosed both intelligently and manually. The intelligent diagnostic method requires the establishment of an expert knowledge base, applies inference engines (such as the fault tree method) to identify and locate fault spot, and takes maintenance measures while creating maintenance work order. However, in

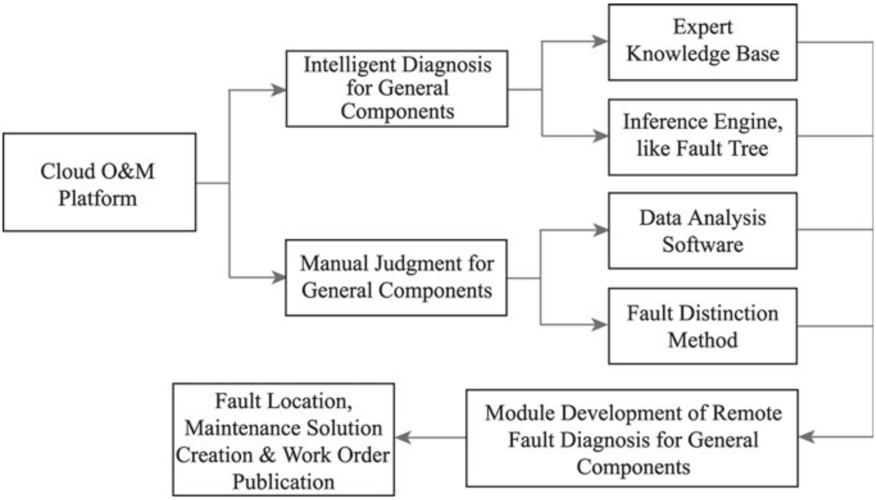

Fig. 6.11 Technology roadmap of the fault remote diagnosis system for general mechanical components

the manual judgment, the fault spot location relies mainly on data analysis software and fault distinction method.

The aim of the wind farm intelligent O&M cloud platform is to build a remote intelligent diagnosis expert system based on expert knowledge base and inference engine. Comprised of knowledge base, inference engine, comprehensive database, human–machine interface, interpretation program, and knowledge acquisition program, the expert system is a knowledge base or rule generation system, with the knowledge base and inference engine being the core.

The knowledge base is an important part of the expert system and is a relatively independent, which includes facts and rules. We can manage the knowledge inside the knowledge base using the program.

As another important part of the expert system, the inference engine performs fault diagnosis and inference using the established facts and rules stored in the knowledge base of the expert system. The order and the process of reasoning can be determined according to the fault-related information suggested by users.

The comprehensive database is used to store the relevant fault information necessary for the running process and the generated fault information. The information includes descriptions of the problems, inferences about the intermediate faults, and records relating to interpretation processes.

The knowledge acquisition program can obtain the required knowledge from domain experts, and of course, literature. The quality of expert system program depends on the quality of knowledge acquisition program. According to current trend, it is difficult to autonomize the knowledge acquisition program, highlighting the difficulty of developing a full-fledged expert system, thus becoming the "knowledge bottleneck" problem of expert system research. In order to have a complete system of knowledge base, it is necessary that knowledge engineers and domain experts form long-term cooperation have thorough and continuous discussion on rules, concepts, and formats, and finally, realize the unity and accuracy of knowledge with the help of expert system.

The human–machine interface software can accomplish the interchanging conversion of fault information. Ordinary users without a degree in computer science or artificial intelligence are still used to natural language, spreadsheets, or other relatively simple forms, in the process of providing fault-related information to the system. However, another conversion method, i.e., intelligent language programming, is used inside the system. Therefore, a connection method is demanded to convert these two forms, and that is the human–machine interface, through which communication happens between domain experts and ordinary users. The expert system is an intelligent computer program, so the interpretation program, being an indispensable part, plays an important role in setting it apart from the traditional systems. Its purpose is to make it easier for users to accept the reasoning process and the conclusion, which benefits both the user and the system itself, bringing convenience to system maintenance and knowledge sharing.

The wind turbine fault diagnosis expert system is essentially composed of knowledge base, inference engine, comprehensive database, human–machine interface, interpretation program, and knowledge acquisition program, as shown in Fig. 6.12. The online monitoring system monitors the objects in working area in real time. When a feature value of an object exceeds the standard, the online monitoring system will capture this change. At this moment, the fault diagnosis system is triggered

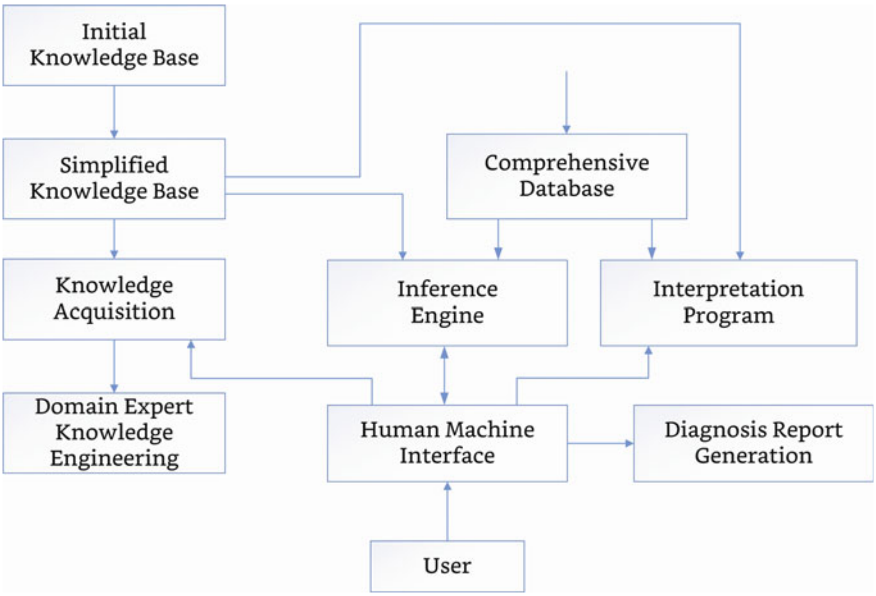

Fig. 6.12 Framework of fault diagnosis expert system for mechanical components

to start the fault analysis. After that, the wind turbine fault diagnosis expert system is launched to analyze the fault symptom, perform diagnosis, provide suggestions for prevention and treatment, and finally, generate diagnosis report.

(4) Intelligent Routine Inspection

Based on the state evaluation and the fault diagnosis results, it is able to formulate wind turbine maintenance plan and take preventive maintenance measures, transforming passive and regular routine inspection into preventive and intelligent routine inspection. The intelligent O&M cloud platform runs online and in real time, and the operation personnel at headquarter monitor the operation status of the wind turbines for 168 h a week, without a single break. After the wind turbine has a warning or fault information, the system will trigger the alarm immediately and issue a maintenance confirmation request, making way for a quick response of the operator to the wind turbine fault. For the pre-defined ordinary faults, the system will issue maintenance work orders to the operation and maintenance personnel on-site. Relying on the technology of Internet+, the O&M personnel will receive real-time notice message via mobile phone client and, through maintenance beforehand, prevent the wind turbine from fault stop or fault escalation.

Figure 6.13 shows the intelligent inspection procedure of preventive maintenance realized by technical support platform (standard manual) covering condition monitoring, weather window, and maintenance strategy.

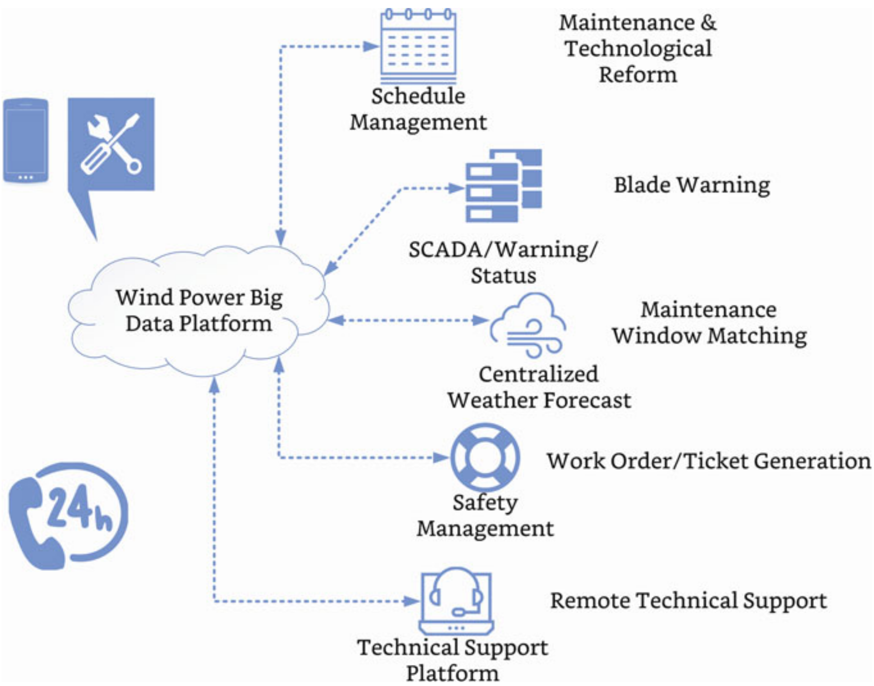

Fig. 6.13 Blade intelligent routine inspection procedure

(5) Operation and Maintenance Management

1) Inventory Management

The wind farm intelligent O&M cloud platform automatically sets and optimizes a reasonable safety stock and reduces unnecessary inventory cost according to the situation of company-level inventory, regional-level inventory, and wind farm inventory, as well as the O&M data and patterns. When fault maintenance declines, spare parts consumption and its inventory level will be further reduced. When the spare parts inventory exceeds the limit, an alarm will be given and automatic purchase will be triggered, thus the on-site O&M personnel will never worry about the spare parts shortage.

At the same time, given the historical inventory situations and the wind farm spare parts consumption, combined with the wind turbine status data, using the machine learning method, it is able to predict the future usage of various spare parts and complete the procurement in advance. In the way, the situation will be avoided when no spare part is available during the fault time, leading to prolonged downtime and increased power loss.

2) Work Order Management

The wind farm intelligent O&M cloud platform provides the operation and maintenance personnel with clear fault point diagnosis information, while the intelligent wind farm management system provides explicit information about the spare parts and tools required for maintenance the operation, pushes the O&M guidance or other related O&M work orders as reference, and has functions historical work order query. Consequently, it is able to reduce the time cost of maintenance work caused by being unfamiliar with maintenance methods, increase the effectiveness of work, reduce the frequency of maintenance and repair, and in addition, arrange the maintenance and troubleshooting work for power-limiting or no-wind period, cutting the power loss as more as possible.

By sending warning work order through the platform, the operation and maintenance personnel can prepare the necessary tools, process documents and spare parts in advance, carry out routine inspections with minimal impact on power generation, and record fault treatment in detail via mobile terminal as soon as possible, for the use of decision making by others.

By sending fault work order through the platform, tracking the fault processing situation in real time, which includes the progress, result, and the personnel, it is able to achieve comprehensive fault management.

3) User Management

The wind farm intelligent O&M cloud platform is open to visitors, staff, and managers. For visitors, the system will display basic information such as detailed wind turbine information, power generation statistics, and fault statistics. Visitors can view the information on wind turbines belonging to different wind farms or regions, and by adjusting the parameters, observe statistical information such as power generation of wind farms and wind turbines. Besides the basic information, the staff can obtain data on wind turbine operation, operation and maintenance, meteorology, inventory, etc., utilize the data for knowledge modeling, build the expert system, and perform data mining tasks. Managers can log into the system server for managerial operations, such as using the wind farm intelligent O&M cloud platform to scientifically dispatch operation and maintenance tasks, and allocating the corresponding resources, to achieve the goal of remote management.

(6) Web Publication

Through the Internet + solution, wind farm condition monitoring information, fault diagnosis and warning information, and fault treatment information can be displayed in real time on the PC terminal and the mobile terminal. Analysts and experts can view large amount of data on wind turbine operation, O&M, meteorology, inventory, etc., to perform fast, accurate, and thorough analysis on the multi-aspect data, such as the overall situation of wind farm operation, power loss, full life cycle data of wind turbine components and O&M records, hence the swift and precise decision making. The O&M personnel can obtain the warning and fault information through the mobile terminal in real time and quickly implement the fault maintenance solution to reduce the downtime of the wind turbine.

3. Critical Technologies of Cloud Platform for Wind Farm Intelligent Operation and Maintenance

Judging from the functional and structural characteristics of the intelligent wind farm O&M cloud platform, its construction still faces great challenges and is in urgent need of support from numerous advanced technologies.

(1) Advanced data acquisition technology

The system regards the wind turbines in wind farms as the main monitoring object. The comprehension of the wind farm operation status by intelligent O&M cloud platform depends on the accuracy and timeliness of operation data acquisition performed by sensors and other data collection devices distributed on the wind turbine. Therefore, it is necessary to rely on advanced data acquisition technology to collect various indicators accurately and in real time, providing reliable data source for procedures afterward.

(2) Advanced remote data communication technology

Currently, in the field of industrial data transmission, most of the applications are wired communication. Although economical and practical, it prevents the application scenario from expansion. With the development of communication technology, the application of wireless communication networks in industrial data transmission is increasing. If the wired and wireless data communication networks can be combined to exert their advantages, respectively, through proper and reasonable application, the efficiency of data communication would definitely be improved and the scale of the application of wireless data communication network would be broadened. Advanced remote data communication technology can ensure the timeliness, accuracy, and security of the normal running of intelligent O&M cloud platform.

(3) Advanced fault warning and diagnosis technology

Timely and accurate fault warning and diagnosis can enable the maintenance personnel to make appropriate adjustments at the early stage of the fault and carry out corresponding inspection and maintenance to avoid huge losses of the entire wind farm. In order to achieve accurate fault warning and diagnosis, and to formulate timely and reasonable maintenance plan, it is necessary to apply advanced fault warning and diagnosis technology based on intelligent algorithms to process the monitoring data.

(4) Advanced database technology

Currently, there are mainly three representative achievements of the database technology development: The first one is to organically combine the artificial intelligence and database technology to form a knowledge base system, which makes the management and search of data more humanized, expands the reasoning ability of the database system, and improves the query efficiency of the database by introducing semantic knowledge; the second one is the distributed database system, that is, making each server process the data independently, which saves the server storage space, breaks the restriction of storage space to the database, allows the database to scale up, and meets the needs of users at the extreme; the third one is the active database, which can adjust the operating state automatically to ensure the stable operation of the database. With the development of database technology, if the database can support various Internet applications, it will certainly provide well-grounded technical support for the intelligent O&M cloud platform.

(5) Refined Internet technology

The construction of intelligent O&M cloud platform could promote the sharing of diverse types of data in wind farms, which requires support from refined Internet technology. Meanwhile, in the process of data transmission and information communication, information security must be emphasized. It is necessary to establish strong network firewall and to encrypt the transmitted information. In conclusion, the construction of intelligent O&M cloud platform demands for reinforcement of refined Internet technology.

6.3.3 IT in Energy Management System

1. **The Composition of new type energy management system**

The traditional energy grid has various energy sources operating independently with electric and thermal energy as the main part, which has the feature of a relatively simple operation model and the small amount of information interaction. After application of the technology like big data, it is a new type of energy management system that embraces a distribution platform based on the smart electric network, a trading platform based on the e-commerce network, various hardware containing energy storage equipment, electric car and intelligent electric equipment, and the correlated service include Internet finance, carbon trading, energy efficiency management and monitoring, which could expend the distributed renewable energy with the multi-application on the electricity area, such as end-to-end transaction, power dispatching, and subsidy settlement in real time. The energy management system is an important component ensuring the safe and reliable operation of a new type of energy network. Compared with the traditional network, this new generation of intelligent energy management system, with the advantages of decision making and collaboration, is bond to realize the acquisition, processing, and analysis of energy information in real time (Zhang et al. 2016).

2. **The function of the new type of energy management system**

The apparently different characteristics between the new type energy network and the traditional energy network are shown in Table 6.1.

As described above, a new type energy network could plan, design, operate, and optimize the multiple energy systems which consist of electric, gas, and heat energy, because of the coupling between the energy unit in the distributed terminal and concentrated energy supplying network. To realize the purpose of the energy conservation and sustainable development, it is available to thoroughly couple the energy, resources, and information together, by considering the local condition of energy, resources, and environment, respectively, and matching and balancing the coordination of supply and demand dynamically.

Table 6.1 Functional comparison between the net-type energy Internet and the traditional energy network

	Tradition energy network	Energy Internet
Multi-energy	Independent operation of the electric and thermal power	Cooperative control of multi-energy
Demand-side	Rigid load, consumers as the energy receiver	Responsive flexible load, large-scale distributed energy integration, consumers might be as an energy producer
Electricity grid	Main AC power	AC–DC flexible power grid, widespread application of energy router
Load balance	Spot balance	The space and time transformation of energy based on various energy storage technology
Operation model	Electricity sale from power supply company Heating fees from the heat supply company	The sale of cooling, heating, and power from the local power supplier
Information	Less information, simple decision	Adapting big data and cloud computing technologies

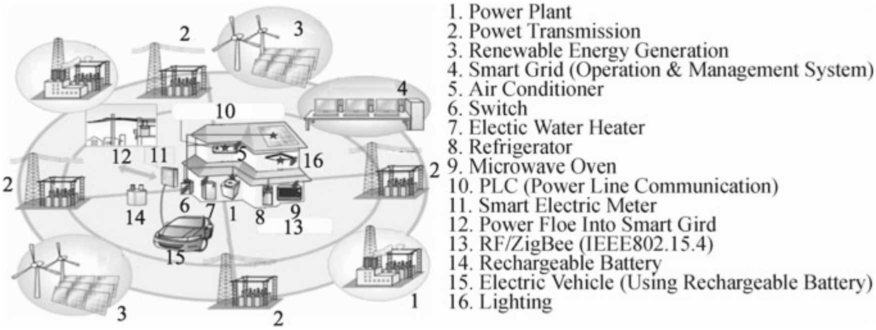

Fig. 6.14 New type of energy system based on Internet

In this new combined structure model of energy supply, various energy technologies are integrated due to the reasonable allocation of all kinds of resources and energy (Fig. 6.14).

Specifically, among the whole life cycle, it is necessary to start from four links of energy use, such as production, storage transportation, application, and regeneration.

Consequently, this new model could increase the utilization efficiency of energy, reduce the emission of pollutant, and increase the level of assurance of energy system and intellective level of energy supply system. In the long term, the local economy and the residents of this area could be developed and get benefit from the safe, stable, and high-qualified energy system, respectively.

3. **The key technology of the new type of energy management system**

The new type of energy network is based on Internet technology, which mainly involves cooperative control technologies between multiple energy, composite energy storage application technology, active power distribution technology, and composite energy management technology.

(1) Cooperative control of multiple energy

The output power of the renewable energy, such as photovoltaic (PV) and wind power, is volatile and intermittent. When these energy resources account for a large proportion (10–20%), the fluctuation of the output would obviously influence the stabilization of the whole system consequently. To stabilize the random variable output power of the renewable energy and increase the adopt capacity of the grid, the cooperative control of multiple energy in the power supply plays an effective role (Wang et al. 2014). Specifically, the cooperative control of multiple energy systems aims to increase the output power, utilization efficiency, reduce the peak load capacity, and increase the power supply stability by combining the power source, controllable load, and storage system together. As a whole, this system could realize the previous goal when participating into the operation and dispatching of the power grid by coordinating and dispatching the power flow at the generator, the load, and the storage system.

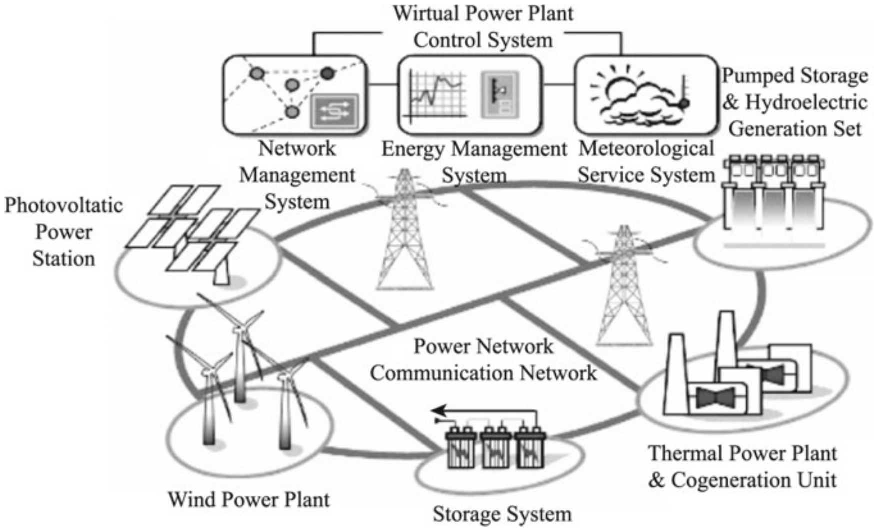

Fig. 6.15 Multi-energy coordination control and operation system

As shown in Fig. 6.15, under the strategy of the cooperative control of wind, PV, and storage system, the loads and the power generation side could be effectively controlled, while the charging and discharging control of storage system are optimized. Specifically, to achieve the goal of a qualified electric system, the application of Internet and data mining technology is used to forecast the PV and wind power output in the short and long terms. Additionally, the real-time and historical data of the grid on both the generation side and receiver side could be used to analyze the result. Except for the above-mentioned means, the cooperative control strategy is also related to the charging and discharging model, life model, and operating condition model of the storage system.

(2) Composite energy storage application technology

With the development of energy Internet, the role and status of energy storage experience outstanding change. Based on the application of energy storage on the power system, the function of energy storage will be further expanded (Li et al. 2015).

In the power system, the energy storage system mainly focuses on power smoothing, peak-shaving and valley filling or peak load shifting of renewable energy, and power quality control of the distribution network.

Energy storage technology can be of several types based on their presentation of energy. According to local environmental conditions and different system requirement, the type of energy storage could be varied or in a form of comprehensive utilization of various storage types. Among these, the technology of the Internet plays a crucial role.

For the battery storage system, for instance, it is mainly divided into energy type and power type. Energy type is mainly used for peak load shifting and other storage systems with long charging time, low charge and discharge rate, and stable charge and discharge power. In contrast, the power type is mainly used for power smoothing, frequency control, and other situations with the characteristics of fast response speed, high charge and discharge ratio, and power change with high speed, etc. According to requirements of battery performance in the various scenario, the operation performance and the cost of the entire storage system could be improved, which is premised on the charge and discharge control strategy of the customized configuration of the composite energy storage system. This strategy is designed by the energy management system in accordance with the requirement of various scenarios.

Due to the current high price, the operating loss of battery capacity, reducing life and the current limitation of charging and discharging processes, it is necessary to estimate the battery capacity and optimize the dispatch between the battery storage system and the wind power generation, before installing the battery, which is mainly based on the Internet technology and mathematical scheme. Taking the combination of battery storage and wind power generation as an example, the applications of Internet technology include:

(1) Optimization capacity estimation

The optimal capacity ratio of the battery is directly related to the battery selection, cost, operation data in the wind farm and the coordinated control strategy of the wind–storage hybrid system. These related elements mentioned above are all needed to set the optimal battery capacity configuration by solving the economic benefit model of battery life.

(2) Optimal scheduling algorithm

After selecting the battery, making a decision on the scheduling of the battery and wind turbines is necessary during the process of the coordinated utilization of these two systems. Firstly, the prediction of wind power generation needs the forecast information from the weather and the history data of wind turbine generation, respectively. Moreover, it is available to obtain the strategy of optimal economic scheduling strategy based on maintaining the battery life. Specifically, the optimization model needs to base on the elements of wind power forecast, battery status information, battery life model, charging and discharging model, and several constraints.

Figure 6.16 shows a composite energy storage system composed of the lithium-ion ferrous phosphate battery and the lead-carbon battery system. Based on the amplitude of the power fluctuation, frequency, and the wind power curtailment factors, both the total capacity of the energy system and the percentage of different battery storage capacity could be confirmed, respectively.

(3) Active distribution technology

The one-direction power flow of traditional distribution network flows from top to bottom. Due to the fact of mass distribution energy integration, the bilateral power flow would not only exit in the low-voltage side but even the medium-voltage side. As shown in Fig. 6.17, most distribution sources exchange power is based on the

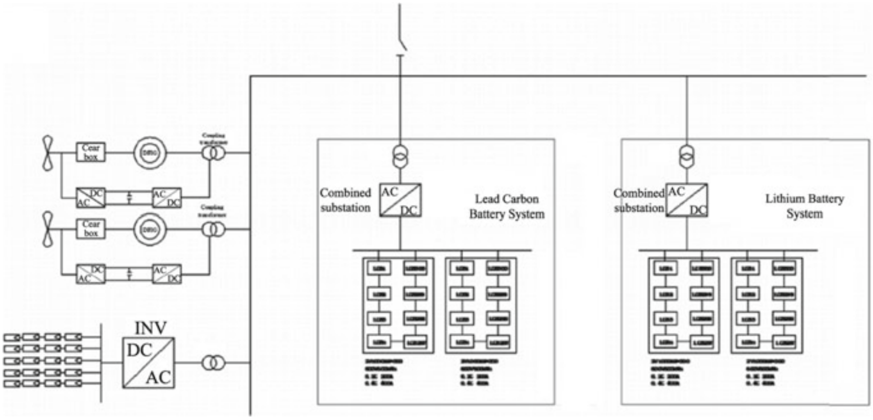

Fig. 6.16 Composite energy storage system

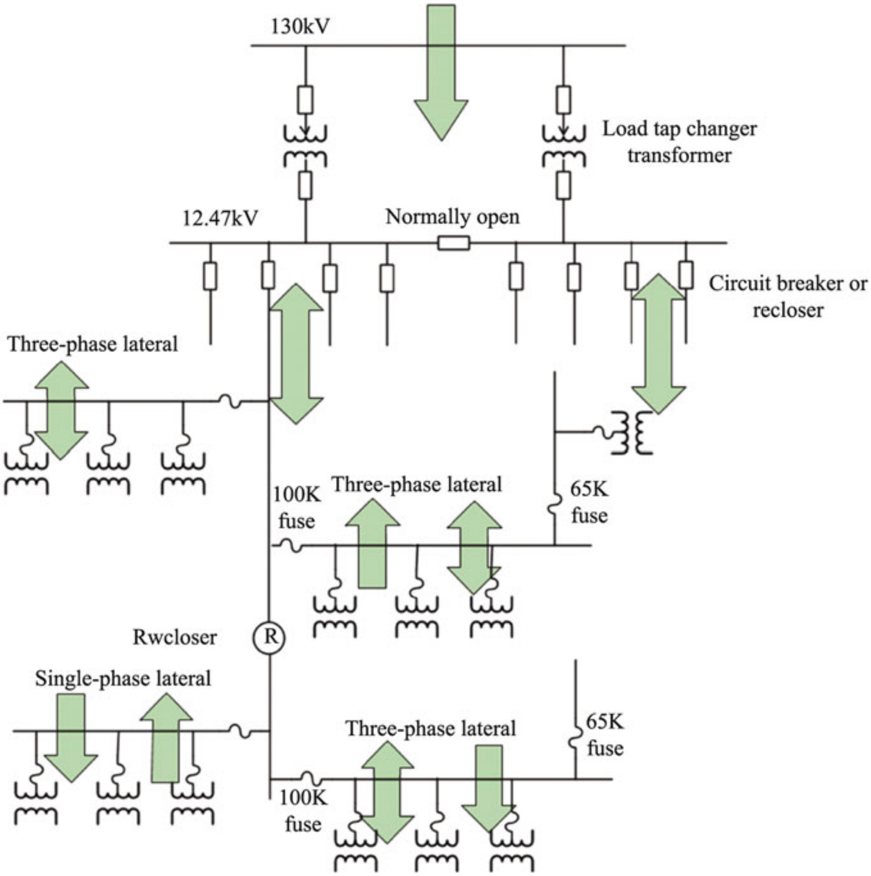

Fig. 6.17 Bilateral power flow of distribution power system

power electronic converter, which certainly could influence the stability of the network operation and the power quality apparently. However, the active distribution technology could increase the existing capacity of the renewable energy in the distribution network through Internet technology.

Figure 6.17 shows the basic structure of the active distribution system. It realizes the active management and planning of distribution network with the help of Internet.

(4) A comprehensive energy management system

A comprehensive energy management system includes load management, energy consumption at the terminal, and the system optimization of the operating system. The basic structure of EMS based on Internet technology is shown in Fig. 6.18.

Load management focuses on the short-medium prediction of power usage of the load with technologies of sensors and communication. Specifically, when the centralized control system collects, analyzes, and saves the data of active power, inactive power, power factor, frequency, and energy consumption statistic, it is possible to make the prediction on the basis of the obtained general law of power usage. With results of the forecast and the significance rank of load, EMS could make category management and schedule decision, respectively.

The energy consumption system at the terminal focuses on the proper allocation of the four types of energy: electricity, cooling, heating and gas supply, and maximizing the energy system efficiency and the economic benefit.

The construction of an energy trading platform is based on various strategies and data analysis technology. Specifically, it takes advantages of the wind–PV–storage–

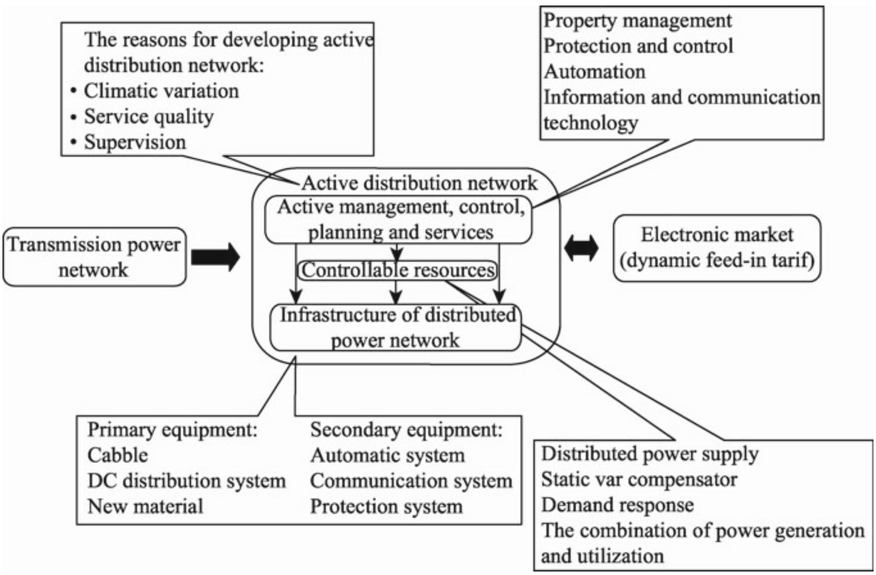

Fig. 6.18 Basic structure of active distribution system

load cooperative control, the operation data analysis of distribution system, electricity consumption analysis, load management, charging and discharging control strategy of the comprehensive storage system, cooperative control of comprehensive energy about the electricity, cold, heat, and gas energy between demand and supply sides. Besides, to build the complete models, such as the system energy efficiency model, resources allocation model, systematic economic model, it needs to use the Internet and data mining technology to deeply dig and analyze the mass data on the supply and demand side of systemic energy, and research, analyze and verify the historical data, real-time data, and forecasting data, respectively, in the meantime. Meanwhile, according to analyzing data, designing systemic scheme, and optimizing the capacity allocation and control strategy, the closed-loop system which includes design and development, data analysis, operating optimization, and design-development optimization, could be built.

4. **Demonstration project**

In the project of Zhongdan Ruihao Wind Farm, the Ming Yang Group has developed a networked microgrid system based on the cooperative control strategy between wind power and storage system. With the control on charge and discharge of storage system, the output power of wind turbines could realize the peak power shifting, guarantee the wind power accommodation, and increase the project benefit.

The basic structure of this microgrid system is shown in Fig. 6.19. In this project,

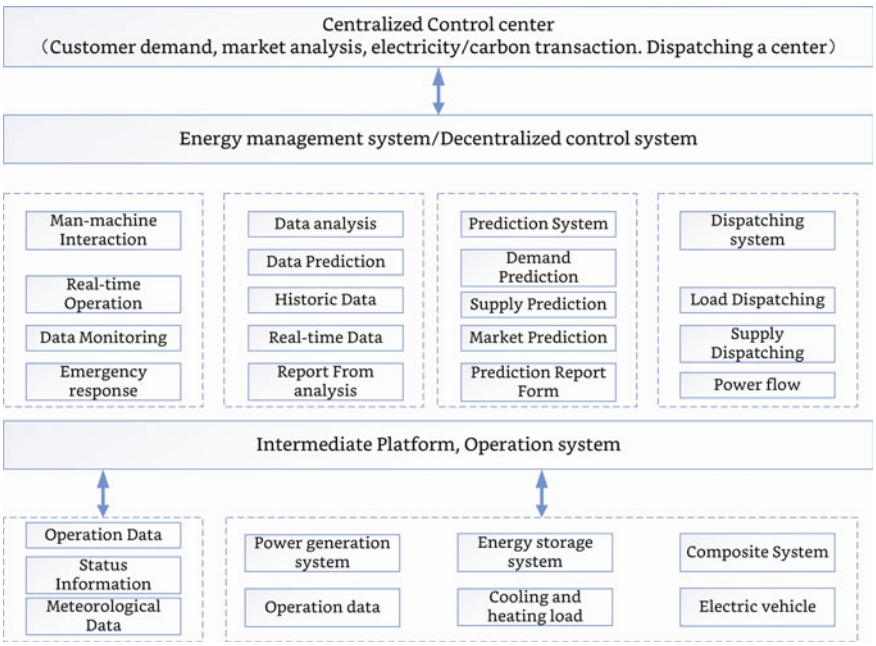

Fig. 6.19 Basic structure of energy management system based on the Internet technology

a MY-1.5WM wind turbine with lead-carbon battery storage system as an example applying the coordinated control based on the wind power technology and storage technology. It could rely on the charge and discharge control of storage system to realize the peak power shifting of output power from the wind turbine, the wind power smoothing, and the decreasing loss owing to the curtailment of wind power. In detail, to execute the instruction from the superior interface, an EMS based on the centralized control platform takes advantage of Internet, data mining, mathematics scheme, and other technologies, to fulfill the requirement of the overall dispatching between the wind energy storage and the Zhongdan Wind Farm, optimizing the operation and increasing the revenue of project investment, respectively.

In this project, wind turbines as the power generation unit could transform the captured wind energy into electricity power. In contrast, energy storage system plays a role in coordinating wind turbine output and the dictation of allowed power output. When the output of wind turbine is larger than the permitted output power for the grid (limiting power generation situation), the extra power is used to charge the storage system. On the other hand, when the limiting power generation situation is canceled, the storage system would discharge the storage power to the grid, thus fulfilling the peak power shifting function of wind power generation. The Battery Management System (BMS) mainly focuses on managing the battery cells and battery cell stacks. According to the characters of different level, each battery group could output power equally in optimal working condition, which owes to an effective management including balancing, alarming, and protecting. In detail, this management premises on computing and analyzing both the parameters and operation condition of different battery level, cells and stacks, respectively. EMS combines predicted weather information and historic wind power generation data to forecast the wind power generation for a period of time. Considering the related information, such as the dispatching instruction laws of the grid, the battery situation, the usage model of the battery, it is available to balance, instruct, and manage the charging and discharging power of the battery and the output power of the entire wind farm, thus reducing the power loss as far as possible by curtailment of wind energy under the premise of the battery life maintenance.

6.3.4 Concluding Remarks

The cooperation of Internet and wind power system would eventually lead to the intelligentization of traditional wind farms. In particular, the precision of wind power prediction could be considerably enhanced with the help of Internet technology so as to provide decision-making evidence for wind farm scheduling and energy dispatching. In regard to operation and maintenance of the wind farm, the application of IT could prolong the wind farm life and reduce operation and maintenance cost . Moreover, the combination of Internet and EMS could transform the traditional wind electricity operation mode to the energy Internet mode, which finally results in a better intelligent, economic, and efficient wind farm energy management.

(Q. Y. Zhang, X. Y. Zhang)

6.4 Wind Turbine Reliability Design

In 2016, the Chinese Government released a document to promote reliability design in major areas. Reliability design has become one impetus for technical innovation to guarantee product quality and brand influence. Wind energy industry has grown one of the most influential high-end manufacturing sectors with more than a decade of development. Reliability of wind power equipment plays a pivotal role in the sustainable and healthy development of wind energy industry through quality improvement, cost reduction, market competition, and international cooperation. Therefore, the present Sect. 6.4 is especially concerned with wind turbine reliability design.

6.4.1 About Reliability Design

1. **Definition of Reliability**

The reliability means the ability that realizes a defined function under the specified condition in scheduled time. Actually, reliability can be divided into basic reliability and mission reliability according to the period of assessment. It is also divided into inherent reliability and operational reliability according to operation conditions.

Basic reliability means the fault-free working ability under specified condition in the scheduled time. The basic reliability reflects the product requirements for maintenance resources. The basic reliability value can be obtained by statistics and analysis of life cycle and related malfunctions. Mission reliability means the ability of functionality realization within the prescribed mission. The indicator of mission reliability is Mean Time between Operational Mission Failures (MTBOMF); it is an important parameter to judge whether a task can be completed.

Inherent reliability is the reliability under the ideal condition and maintenance support, depending on designer and manufacturer while the operation reliability is the reliability under actual operation.

Reliability is one of the essential indicators for product quality. It will ensure the technical and economic feasibility of the products, and determine the market competitiveness. As Qian Xuesen pointed out decades ago, the product reliability comes from design, manufacture, and management. Reliability design is the key points to ensure the reliability of products.

The reliability design of wind turbine is a comprehensive balance of performance, reliability, maintenance, economy, and other factors of the wind turbine. Some special technologies and methods of reliability design are applied to wind turbine products to optimize the design and meet the reliability requirements of wind turbine.

2. **Reliability Indicators**

Reliability indicators can be used to characterize the wind turbine reliability. The indicators are shown in Table 6.2.

3. **Contents of Reliability Design**

Table 6.2 Reliability parameters

Indicator	Definition
Mean time between inspection (MTBI)	Average time between two regular or irregular maintenance
Failure rate	The total expended number of failures within an item population, divided by the total time by that population, during a particular measurement interval under stated conditions
Hazard rate	Instantaneous failure rate. At any point in the life of an item, the incremental change in the number of failures per associated incremental change in time
Mean time between failure (MTBF)	A basic measure of reliability for repairable items. The average time during which all parts of the item perform within their specified limits, during a particular measurement period under stated conditions (RAC Toolkit)
Mean time between maintenance (MTBM)	A basic measure of reliability for repairable fielded systems. The average time between all system maintenance actions. Maintenance actions may be for repair or preventive purposes (RAC Toolkit). An alternative definition: The time (i.e., operating hours, flight hours) between the need for maintenance actions to restore a system to fully operational condition, including confirmation that no fault exists (a no-defect maintenance action). This parameter provides the frequency of the need for maintenance and complements the labor hour parameter to project maintenance workload. This parameter is also used to identify unscheduled maintenance (MTBUMA) and scheduled maintenance (MTBSMA)
Mean time between repair (MTBR)	A basic measure of reliability for repairable fielded systems. The average time between all system maintenance actions requiring removal and replacement or in situ repairs of a box or subsystem
Mean time between critical failure (MTBCF)	A measure of system reliability that includes the effects of any fault tolerance that may exist. The average time between failures that cause a loss of a system function defined as “critical” by the customer (RAC Toolkit)
Mean time between operational mission failure (MTBOMF)	A measure of operational mission reliability for the system. The average time between operational mission failures which cause a loss of the system’s “mission” as defined by the customer. This parameter may include both hardware and software “failures”
Mean time to failure (MTTF)	A basic measure of reliability for non-repairable systems. Average failure-free operating time, during a particular measurement period under stated conditions

Data Source Blischke and Prabhakar Murthy (2000)

Reliability design of wind turbine is the application of reliability theory, technology, and methods in this area. It is a comprehensive balance of performance, reliability, maintenance, economy, and other factors of the wind turbine. The determination process of the function indicators of wind turbine and its components is to optimize the design and satisfy the reliability requirements. Reliability design is the expending and perfection of traditional design measures. It considers safety probability, fault prevention, and maintenance accessibility, besides the technological features. In terms of technology, reliability design includes system reliability design, circuit reliability design, structure reliability design, mechanical reliability design, and software reliability design.

(1) Reliability Design Process

Reliability design includes six critical process, which are identification, design, analysis, validation, and monitoring and control. The design contents include identification of reliability targets, establishment of the reliability model, reliability prediction, reliability allocation, detailed design, reliability analysis and evaluation, reliability quantitative analysis and design optimization, reliability testing and improvement, etc.

1) Identify Reliability Targets

The reliability targets are determined by requirement of client and market, manufacturing level, and economical efficiency. The reliability requirement and target can be quantitative analyzed by collecting the datum of the congeneric product according to the operation condition. The analysis can be systematic, in the assembly, at components, or on malfunction.

Firstly, it is necessary to determine the operating and environmental conditions of the product. These conditions are confirmed by user survey, environmental testing, and sampling. The requirement is determined by agreement, industry benchmark, competition analysis, expectations of users, cost, safety, best practice, etc.

2) Reliability Model Establishment

Reliability model is composed of reliability block diagram (RBD) and formula of reliability indicators. The RBD is used to describe the reliability logic relations between system and components. The formula is used to describe the reliability quantitative relation between system and components.

3) Reliability Indicators Allocation

When the reliability goal is defined, the system reliability indicators need to be allocated into the components or subsystems, according to the structure, type and characters of the product. Before the allocation, the system reliability indicators should be calculated, to predict the reliability, according to the component reliability datum in the scheme. If the calculated reliability meets the requirement of system reliability indicators, the reliability measures will not be allocated. Otherwise, the measures of backup system and component reliability enhancement should be carried out to enhance the system reliability. The method of reliability allocation includes:

Agreement method distributes same reliability to every unit. According to the system complexity, it can be divided into three classes, series system, parallel system, and hybrid system reliability allocation.

Method of proration is also called relative failure rate method and relative failure probability method. The reliability can be distributed into the units according to predicted failure rates. The method fits for the series system.

AGREE method is a complete synthetic approach. It considers the complexity, importance, operation time, and relation between them and the system of the units and subsystems. This method fits for the system with constant failure rate.

Lagrange multiplier method introduces a Lagrange multiplier to combine original objective function and constraint condition of constrained optimization problems to a new objective function called Lagrange function. The unconstrained optimal solution of the new function will be the constrained optimal solution of original function.

Dynamic programming method's methodology of finding the optimal solution is different from the differentiation for finding function extreme and the variational method. It resolves multi-variable decision-making problems by resolving some sub-problems to get optimal solution. The problem with a mumble of variates will become an order decision problem that each independent variable is solved sequentially. This method makes the optimal decision using a series of recurrence relation. The computational logic is simple, and fit for the computer calculation, so this method is widely available in the actual project.

4) Detailed Design

The designer uses appropriate structure and material, and calculates accurately the designing parameters, according to the reliability requirement and operation condition. The main mission is to select the reasonable backup system, failure mode and response calculation formula, and calculation method. Detailed design must consider the measures for environmental stress tolerance, such as influence of temperature, humidity, vibration, and some other field. In addition, the maintainability design should ensure product faults to be easily detected and solved. The strict requirements should be set for the reliability indicators of the purchased parts and cooperation part.

5) Reliability Analysis and Evaluation

In this stage, the reliability indicators should be roughly calculated by using the physics of failure, simulation model, testing datum of related products and reliability prediction method based on standards, according to the engineering evaluation and expert opinion.

6) Reliability Quantitative Analysis and Design Optimization

In this stage, the prototype is tested fully and analyzed effectively, and the preliminary work is assessed according to the test results. The design is optimized by iteration of experimental results and test result analysis, and repeating test is conducted. The products life can be predicted, and reliability will be enhanced by detecting the product defects in the reliability assessment.

By reliability test, analysis, and assessment, the rationality of the design scheme will be checked. The existing problems and suggestions for improvement will be feedbacked to design department so as to improve the original design. This stage of work can be repeated to perfect the original design. After technical review, formal design process and trial production will start.

7) Reliability Verification

At this stage, quantitative accelerated life test (QALT) and life data analysis (LDA) technology will be used to verify that the reliability goals which can be realized with the lowest cost and the product can be mass manufactured. The uncertainty from the production (material, production process, etc.) will be assessed, to ensure the design can be realized under existing technical and process status.

(2) Reliability Design Methods

1) Simplify and standardize. The matured technology, structure, and standardized parts are employed in the design, and the components are minimized to realize the reliability goals of the wind turbine.
2) Redundant design. In the design, the standby unit or system is used to ensure the reliability of the system.
3) Derating design. Equipments and components work under lower stress than rated values to ensure safety and reduce failure rate.
4) Environmental Enduring design. According to the predictions on the type and severity of the operation condition and its influence on the product, technological measures are employed to strengthen the tolerance and adaptability to the environment. The measures can be verified by environmental test or durability test, etc.
5) Thermal design. For electronic, electrical, and mechanical products, excessive work temperature may cause failure and excessive in failure rate. The thermal design is to reduce the heat or enhance heat dissipation to ensure the temperature rise within the specified range.
6) Maintenance design. Qualitative consideration is necessary for the traditional design in repairability (easy to assemble, remove, replace, recognize, etc.), and the designed maintainable system should meet certain maintainability indicators. Maintenance strategy and maintenance management shall be established.
7) Ergonomic design. Firstly, reliability of the information presented to the operators by system are ensured; secondly, the reliability of instructions, information, or operations from human to the system are ensured; thirdly, the operation environment design makes the work environment suit human physiological characteristics to reduce operator fatigue and the probability of operation failure.
8) Safety design. The products possess high security indices, by assigning the indicators to products.
9) Fool proof design. The necessary steps are introduced to ensure the operator make no breakdown even in the case of misoperation.
10) Fail-safe design. It ensures the security of the system itself and its personnel or environment, when a failure occurs in a designed system.

11) Probabilistic design. The designed product is given a certain degree of reliability, according to the interference model for a failure mode of parts or structures.

(3) Basic Principles of Reliability Design

Reliability design, as a specific design, is subject to the current technical level, development cycle, funds, and other conditions, and it is required to meet not only the performance index but also the reliability index. Reliability design is the synthesis and balance of each design requirement or technical index. The following principles should be followed in the reliability design:

1) Reliability design is not an isolated activity and should make full use of information related to product transportation, maintenance, and operation.
2) Reliability design should take the existing technical level into full consideration and adopt mature, approved, and standard technology as far as possible.
3) A comprehensive understanding should be achieved on the environment and the state of the product in the process of transportation, storage, and use.
4) Reliability design should take full account of manufacturing, assembly and other process requirements and carry out process verification.
5) Quantitative reliability targets, such as establishment of product reliability target, distribution of reliability index, etc., shall be in the whole process of product development and design.
6) The standardized management should be emphasized and strengthened to ensure the reliability of the design.
7) Reliability design techniques are as important as reliability management.

6.4.2 Reliability Design of Wind Turbine

The study of reliability as a discipline originated from the demands of the military sector in World War II. During World War II, Germany introduced the concept of reliability in improving the performance of its weapons. The military departments of USA conducted a number of reliability studies between 1945 and 1950, because the technical equipments often fail. In 1957, the report about "the reliability of military electronic equipment" was published, and the reliability indexes were put forward on test, validation, and appraisal method in the process of production, manufacture, and the reliability requirements during the process of packaging, storage, and transportation. This report is widely recognized as the cornerstone of the reliability work of electronic products. Since then, the research of reliability theory started and gradually developed worldwide. Reliability began to form an independent engineering discipline.

In the 1960s, the demand for reliability became higher because of the complexity of products and the harsh working conditions. Reliability technology quickly spread from the electronics industry to other industrial sectors. Reliability design and management techniques are used from the Apollo spacecraft to washing machines, cars, and televisions.

From the 1960s to the 1970s, the aviation and aerospace industry was promising. Many countries began to carry out research and product development of aerospace, aviation technology and equipment, and its reliability attracted attention of the whole society, and thus it is also made great progress. Many countries have set up reliability research institutes. In the 1960s and 1970s, reliability technology was introduced into automobile, power generation equipments, tractors, engines, and other mechanical products.

Since the 1980s, reliability design has become indispensable in all industries. The reliability develops from military equipments to the civilian products, from electronic products to non-electronic products, from hardware to software, from reliability to credibility engineering including maintenance, test, and security engineering. It transferred emphasis on from reliability statistical test to reliability engineering test. The failure of the product is exposed through environmental stress screening and reliability enhancement test, so as to improve the reliability of the product.

The research on the reliability design of wind turbines started in the 1990s. As the increase of capacity and complexity, it's of great importance to reduce maintenance costs, enhance power performance, and lower electricity costs. Failure mode effects and criticality analysis (FMECA) is applied from aerospace, nuclear power to wind power.

In the early 1990s, the USA, Germany, and other countries began to research the reliability for small wind turbines. In 2004, Sandia Laboratory began to study the relationship between reliability and cost of wind turbine. In 2009, with the support of the US Department of Energy (DOE), the study was initiated on the reliability of grid-connected wind turbines.

German wind energy institute (DWEI) carried out the study of wind turbine operation monitoring project (WMEP). During the period from 1989 to 2006, they collected the operation reports, maintenance, and repair reports of 1500 wind turbines with different capacity, different types, and different installation locations.

In addition, in order to enable offshore wind turbines to achieve similar performance and operation maintenance costs of onshore wind turbines through higher utilization and lower generation costs than current ones, the European Union provided funding for the ReliaWind collaborative research project under framework 7. The project has been implemented for three years, providing practice for the design, operation, and maintenance of highly reliable offshore wind turbines.

Since 1986, the Ministry of Machinery Industry of China has issued a list of six batches of reliability indexes for mechanical and electrical products, and 879 products have been evaluated. In the 1990s, the relevant competent authorities of Chinese government issued the "Regulations on strengthening the design of mechanical and electrical products," which clearly pointed out that the "reliability, economy, and adaptability" tripartite coordination was the basis for the design and appraisal of mechanical and electrical products. The reliability design data and test report must be provided during the new product identification; otherwise, the identification cannot be passed. Nowadays, the view and method of reliability have become the indispensable basis and means of quality assurance, safety assurance, and product liability prevention, and also one of the important contents for Chinese engineers and technicians to master modern design methods. In November 1990 and October 1995, the ministry of machinery and industry held two press conferences to introduce 236 and 159 mechanical and electrical products with reliability indexes. In March 1992, the ministry of national defense science and technology commission commissioned the military standardization center to hold the "non-electric product reliability work exchange seminar" in Beijing. In 2005, content of mechanical reliability was added in the modified standard of GJB450. In the 1990s, the Fifth Research Institute of the Ministry of Electronic Industry introduced the reliability comprehensive stress test into China and developed the first set of domestic temperature, humidity, and vibration comprehensive environmental test equipment. In 1997, Xisha natural environment test station was established. In 2000, the first software reliability evaluation and analysis laboratory with the largest investment in China was established.

With the maturity of large-scale wind power development in China, the risk management and control awareness of wind power development enterprises has been continuously strengthened, and the requirements on the quality and reliability of wind turbine have been continuously improved. Wind power equipment manufacturers have begun to pay attention to the reliability of wind power equipment. In 2012, the Chinese Wind Energy Association (CWEA) organized domestic enterprises to participate in the WindTask33 project of the international energy agency Wind (IEA wind) agreement group, "Reliability data: standardization of wind turbine reliability and maintenance analysis data collection." Driven by the project, the main domestic wind turbine manufacturers such as Goldwind and Envision began to study the reliability design and reliability evaluation technology of wind turbine. It lays a foundation for the research of reliability design.

6.4.3 Basic Information of Reliability Design of Wind Turbine

At present, the research and application of wind power reliability design technology mainly includes wind turbine reliability modeling and evaluation methods, wind turbine reliability data acquisition and analysis technology, and wind turbine reliability testing technology, etc.

1. **Reliability Modeling and Evaluation Methods for Wind Turbine**

Sufficient reliability data and effective analysis method are the precondition of reliability quantitative analysis. Reliability data analysis methods commonly use in the field of wind power include reliability block diagram analysis, fault tree analysis, fault mode analysis, influence and criticality analysis, etc.

(1) Reliability Block Diagram Analysis (RBD)

The reliability block diagram is the logic diagram between the system and the components. It is the graphical representation of the connection relationship between the system unit and its reliability. Reliability block diagram analysis can be used to model system availability and reliability.

RBD depends on the arrangement of boxes and wires to draw the impact of the failure of each part of the system on the functional characteristics. It only reflects the series and parallel relationships among the parts, and is independent of the order of the parts. The reliability block diagram is based on the functional block diagram, but does not reflect the order, and only considers the relations between the parts from the reliability perspective. In some cases, it is different from a structural connection diagram. The reliability block diagram uses interconnected boxes to display the failure logic of the system and analyzes the impact of each component's failure efficiency on the system to help evaluate the overall reliability of the system.

The ReliaWind project has conducted in-depth research on reliability design and proposed the application of RBD method to analyze the reliability of each system of wind turbine, completing the reliability block diagram of Gamesa R80 (1.5–2 MW) and R100 (3–5 MW) two types of wind turbine, as shown in Fig. 6.20.

According to the GJB 813-1990, the establishment of reliability model and reliability prediction and IEC 61078:2006, the reliability modeling using reliability block diagram is divided into three steps:

The first step is to define the product. The important features of the product are described in words, including product name, product model, product composition, brief working principle, and determination of product life profile (the product life profile refers to all the events and time series description of the environment experienced by the products from the date of acceptance to the end of life or the period of withdrawal from use) and mission profile (the mission profile refers to all the events and time series description of the environment, as well as the duration as the product performs its tasks), the failure criterion of tasks, the tolerance limit of important parameters, and the qualitative reliability requirements.

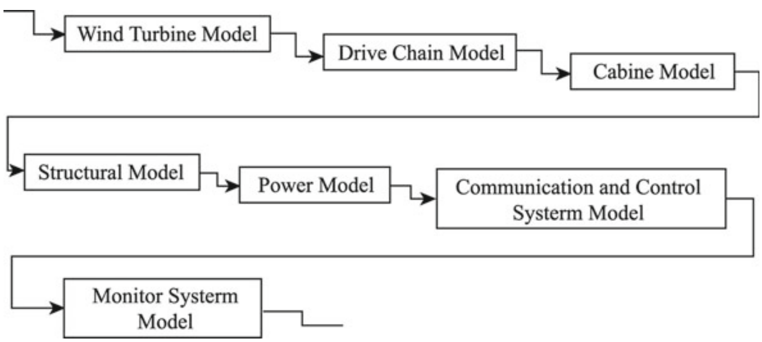

Fig. 6.20 Reliability block diagram of Gamesa R80

The second step is to draw the reliability diagram of the product. The reliability block diagram reflects the logic diagram between the system and the components from the perspective of reliability. It is the graphical representation of the connection relationship between the system unit and its reliability, showing the influence of the normal or failure state of the unit on the system state.

Figure 6.21 is a demonstration of reliability block diagram for a wind turbine provided by ReliaWind.

The third step is to determine the calculation formula of reliability value, that is, the system reliability mathematical model. The reliability mathematical model describes the quantitative relationship between the reliability variables of each unit and the system reliability value, and the reliability index of the whole system can be calculated by using the known unit reliability value (such as failure rate).

(2) Fault Tree Analysis (FTA)

Fault tree analysis (FTA) is a common graphical method of fault analysis, and a logical method for fault events under certain conditions, that used in reliability, security analysis, and risk assessment of large complex systems. FTA uses a special inverted tree logic causal diagram to illustrate how the system fails. Fault tree diagram uses event symbol, logic gate symbol, and transfer symbol to describe the causal relationship between various events in the system. The input event of the logic gate is the “cause” of the output event, and the output event of the logic gate is the

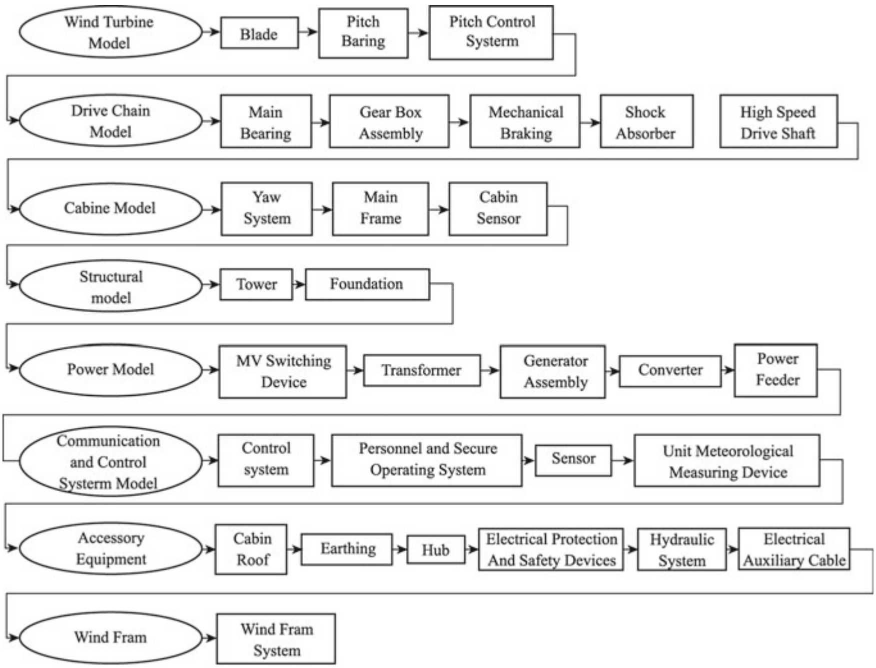

Fig. 6.21 Demonstration reliability block diagram for a wind turbine

"result" of the input event. Logic connects events to represent logical relationships between events. Based on the in-depth study of fault tree analysis methods, the fault tree analysis standards are established, including GJB/Z768A-98, IEC 61025-2006, etc. FTA method is widely used in qualitative and quantitative reliability analysis. FTA can also be applied to reliability analysis and evaluation of wind turbine and components, complex power generation equipment.

In addition, the most basic difference between RBD and FTA is that RBD works in a "successful space," and the system seems to be a successful set. While FTA works in "fault space," the system seems to be a set of failures. Traditionally, fault trees have been used to a fixed probability (i.e., each event that makes up a tree has a fixed probability of occurrence). On the other hand, RBD can be a function of time and other features for reliability. In general, a fault tree can be converted to an RBD, with some exceptions. However, it is generally difficult to turn an RBD into a fault tree, especially for systems with very complex structures.

(3) Failure Mode, Impact and Criticality Analysis (FMECA)

Failure mode, impact and criticality analysis (FMECA) is aimed at all possible faults of the system, to determine the impact of each fault mode on the system work, based on the analysis of fault mode. By finding out the single-point fault, the criticality is determined according to the severity and probability of fault mode. Single-point fault is a local fault that causes a system fault and has no redundant or alternative working procedures to remedy it. FMECA-related standards include: IEC60812:2006, MIL-STD-1629A, etc.

FMECA includes failure mode and effect analysis (FMEA) and criticality analysis (CA). Fault mode is a form of failure of a component or product. In general, it is a fault phenomenon that can be observed. Fault impact refers to the impact of the fault mode on security and system functions. Generally, the fault impact can be divided into three levels: local, upper, and final.

Fault mode and impact analysis was originally a design analysis method to improve product reliability by analyzing the potential failure modes of each component unit of the product and their impact on product function. It is a design and analysis method for the possible preventive improvement measures to improve product reliability. It is proposed as a preventive technology. It has now been extended to the application of product performance analysis, used to verify the correctness of system design, to determine the cause of failure mode, and to evaluate the reliability and safety of the system.

Criticality analysis is to analyze each fault mode in FMEA according to its severity category and probability of occurrence, so as to comprehensively evaluate the impact of various possible fault modes. Criticality analysis is the continuation of FMEA, and it can be qualitative or quantitative.

FMECA is probably the most widely used and effective method of design reliability analysis. FMECA is also widely used in wind power equipment reliability analysis and reliability design.

Compared with FMECA and FTA, FMECA starts from the lowest analysis level of the system (such as element and component level) and goes from the bottom to the agreed analysis level (such as system level), that is from cause to effect. FTA starts from an “undesired event (top event)” of the system and gradually traces the cause of the top event from top to bottom, until the basic event (bottom event), that is from the result to the cause. In actual work, FMECA and FTA are often used in combination to improve the efficiency of reliability analysis of complex systems.

(4) Markov Model Analysis

Markov process-based model is widely used in power system reliability assessment and has become one of the most commonly used wind turbine reliability assessment modeling tools. None of the above methods involves the system going from available to invalid and returning to available after maintenance. In reliability and availability analysis of repairable systems, failure rate and probability of returning to available state, failure efficiency and repair rate, and system effectiveness are concerned. Markov model analysis is widely used to study these phenomena. Sayas and Allan applied Markov model to study the relationship between wind speed and failure rate of wind turbine. McMillan and Ault used the Markov process to simulate the state change of the gearbox, generator, blade, and electronic equipment of the wind turbine.

There are some main constraints to the Markov process:

1) The future state of the system is independent of all past states, except for the closest previous state (current state). This means that only the current state is used to predict the future, and that the past (i.e., the current past state) is irrelevant for predicting the future (i.e., the future state after the present state).
2) The probability of going from one state to another is constant. Random walks are examples of Markov chains. The state of each step in the random walk is the point in the graph, each step can be moved to any neighboring point, and the probability of moving to each point here is the same, no matter what is the before path.

Of course, these constraints are less stringent in engineering applications. This enables Markov model analysis to be used effectively for reliability, security, and availability analysis of the system. However, in practical using, the degree of impact of condition deviation on analysis results should be evaluated.

Markov process analysis needs to be solved by matrix, and even the probability matrix of a very simple system will become very complicated. While computers can be used to solve problems quickly, these complexities are difficult to understand for anyone outside the expert on reliability.

2. **Reliability Data Collection and Analysis Technology of Wind Turbine**

Wind turbine data acquisition and analysis technology is the basis of reliability evaluation and reliability design. Through the statistical analysis of wind turbines running data, the reliability characteristics of wind generator system, subsystem, and component can be mastered, to understand the function of design failure rate based on the operating conditions and the probability, so as to determine the wind power equipment reliability needs and goals.

Data collection and analysis of wind power units and wind farms abroad are carried out earlier. In Europe, standardized, systematic, and transparent wind power data collection has become an important factor driving the development of the wind power industry across Europe. At present, data collection of wind turbines focuses more on the quality and reliability of wind turbines.

Many international institutions engaged in wind power data acquisition and analysis research, mainly including Wind Task 33 Project of IEA Wind, CREW Project of Sandia National Laboratories in USA, IWESWMEP Project of Fraunhofer Institute in Germany, ReliaWind Project of EU, etc. The main IEA Wind Task 33 (Reliability Data: Standardizing Data Collection for Wind Turbine Reliability and Operation & Maintenance Analyses) aimed to identify the generic term, format, and criterion of the data collection (spare part, maintenance, fault and status data) and establish the analysis and reporting procedures. The expected results of the project are the data collection, data structure, and data analysis guidelines for the overall wind turbine fault statistics.

CREW Project of Sandia National Laboratories, collected and analyzed data from ten wind farms with more than ten wind turbines, includes 800–900 wind turbines and total capacity of 1300–1400 MW. The datum of wind farm SCADA system was transferred through the OPC interface to database of SPS Company, and then transferred to Sandia National Laboratories after analyzed by ORAP wind software and generate analysis report finally. The time interval of the acquisition frequency of SPS data is 2–10 s, which becomes the value of 10 min after processing (including average, maximum, minimum and maximum, and standard deviation), wind turbine status and event data. The data collection reaches the level of unit parts. The integrity of data collection is not very well, and the time of data collection is about 30%. The integrity of the set is not very good, and the time of uncollected data is about 30%. According to the obtained data, Sandia Laboratories statistics analyzed the relationship between five key indicators, wind speed and different output time of the unit, the power curve of wind turbines and the proportion of different systems, components and events affecting the availability of wind turbines (Mcmillan 2008; Sandia Report 2011; Sandia Report 2012).

WMEP Project of the Fraunhofer Institute for Wind Energy Systems collected 193,000 monthly operation reports and 64,000 maintenance and repair reports of about 1500 wind turbines. These wind turbines have different capacity, types, and installation locations, making the collected data more comprehensive coverage. The data is divided into basic data, event data, and result data.

Basic data includes the data of wind farms and wind turbines, capacity per unit, rotor diameter, hub height, operating conditions, environmental conditions, topography and landform, and unit type, etc. In the basic data, the data of wind turbines and the components was encoded according to the European Association of Electrical and Power Generation (VGB) standard "VGB-B 116 D2."

Event data is grouped by event attributes according to Guideline B-109 of the VGB standard. The events are divided into 12 groups, including the event type, running state before the event, running state after the event, influence on the unit, influence of breakdown, failure reason, damage mechanism, damage phenomenon, wrong identification, maintenance type, measures to prevent a recurrence, and the urgency of the measures. The results data include the characteristic data of the reliability of different wind turbines, such as MTBF and MTTR.

According to the collected data, Institute for Solar Energy Supply Technology (ISET) analyzes the influence of operation period on the failure rate of wind turbine, the influence of the reliability of each component, the reliability of wind turbines of different power levels, and different external environment on the reliability of wind turbines, the relationship between the cost and the reliability of different type of wind turbines, the weak parts of units and different maintenance objectives (Sandia Report 2010).

ReliaWind Project established a wind turbine reliability database, which recorded 31,500 downtime for 350 units, including 450 wind farms per month. The wind farms were selected according to the following conditions:

- There are at least 15 wind turbines.
- The wind turbine should be variable-speed, variable-pitch wind turbine.
- The rated capacity is not less than 850 kW.

The data comes from the 10-min average data of SCADA system, fault or alarm record, work orders and maintenance records, operation, and maintenance report. Wind turbines and components codes were encoding based on RDS-PP system. The wind turbine is encoded in five levels of the system, subsystem, component, sub-component, and part. Reliability datum was classified into all events, annual failures of wind turbine based on the measurement of the sub-component failure rate, based on the measurement of downtime of the sub-component, wind farm configuration description, and other information (including wind power generation, and the wind turbines life related amount). The basis of events selection is restart of events and causes downtime in 1 or more hours.

3. **Reliability Testing Technology for Wind Turbines**

In the reliability design process of wind turbines, the inherent reliability of products should be determined through reliability prediction, distribution, and optimization design. On the other hand, in the process of design, development, and production, reliability test is needed to ensure reliability. At present, the test items of the whole wind turbine and components are carried out in accordance with the standards can be included in the scope of reliability test.

(1) Testing of Wind Turbine

The testing of wind turbine includes ground test and site test. The site test of wind farm is mainly carried out to test the performance, load, and safety of wind turbines, which provides test data for the type certification of wind turbines and wind turbine design optimization. Test contents and standards are shown in Table 6.3.

The ground test of wind turbines is mainly carried out by using the ground test platform to simulate the time operating load of wind turbines using the simulation technology, and the performance test of wind turbines under the full working condition is realized through the loading device. The test terms include driving chain output

Table 6.3 Wind farm site test project list

No.	Test item	Standards
1	Power performance measurements	GB/T 18451.2-2003 power performance measurements of electricity producing wind turbines/IEC 61400-12-1:2005 power performance measurements of electricity producing wind turbines
2	Measurement of mechanical loads	IEC/TS 61400-13:2001 wind turbines—Part 13: measurement of mechanical loads
3	Measurement and assessment of power quality characteristics	GB/T 20320-2006 wind turbines—Part 21: measurement and assessment of power quality characteristics of grid-connected wind turbines/IEC 61400-21:2008 wind turbines—Part 21: measurement and assessment of power quality characteristics of grid-connected wind turbines
4	Acoustic noise measurement	GBT 22516-2008 wind turbines—Part 11: acoustic noise measurement techniques, IEC 61400-11:2006 wind turbines—Part 11: acoustic noise measurement techniques
5	Safety and functional testing	IEC 61400-1:2014 wind turbines—Part 1: design requirements
6	Grid connection performance test	GBT 19963-2011-technical rule for connecting wind farm to power system
7	Low-voltage ride-through test	NB/T 31051-2014 specification of wind turbine low-voltage ride-through test and distribution projects

power curve test, power quality test, power network fault simulation test (low-voltage ride-through fault simulation, high-voltage ride-through fault simulation, power network unbalanced fault simulation test, etc.), steady and transient load test, vibration simulation and performance test, noise test, fatigue life test, etc. Through the above tests, data can be provided for wind turbine design optimization, performance, safety, and reliability verification.

In recent years, with the development of large wind turbines, the foreign driving chain testing technology of wind turbines has been developed rapidly. The world's leading wind energy research institutions, such as Britain's national renewable energy center (Narec), Denmark Risø DTU National Renewable Energy Laboratory, the National Renewable Energy Laboratory (NREL), Wind Power Research Institute (DEWI), Germany, Spain's National Renewable Energy Center (CENER), and other agencies are set up advanced driving chain and key components test bench.

The increasing capacity of the test bench and the gradual improvement of test items and test functions make the test results closer to the actual operating conditions. The test bench not only gives great support to wind turbine manufacturing enterprises in the research and development of new turbines, but also plays an important role in the testing and certification of wind turbines, improving the reliability of wind turbines and regulating the development of the wind power industry. Among them, Clemson University in the USA, and the National Center for New and Renewable Energy and Romax in the UK have completed the construction of the driving chain test bench of the 15-MW, 6-dof dynamic load wind turbine, respectively. They can simulate the dynamic loads that large wind turbines put on the driving chain in the offshore environment and have been put into commercial operation (Fig. 6.22).

The Chinese domestic wind turbine driving chain test bench is mainly built in wind turbine manufactures. Its function is mainly to meet the requirements of factory inspection of products. The testing capacity, especially the loading mode, is also quite limited.

(2) Testing Technology for Wind Turbine Components

The testing of key components parts (blade, gearbox, bearing, generator, pitch system, etc.) of wind turbine is mainly carried out on the ground full-size testing bench, and the testing of parts performance and acceleration life is carried out according to relevant standards. The National Wind Technology Center of America (NWTC) has completed more than 100 blade fatigue damage tests in the past 20 years, and studied the design concept and the characteristics of the manufacturing process of various blades, that provide the blade manufactures important technical support. In addition, the test bench of the German Blade Test Center (BLAEST) can carry out static experiment, fatigue test and stiffness test of wind turbine blades with a length of 100 m, and control the manufacturing quality of the blades with non-destructive testing technologies such as thermal imaging, acoustic emission and ultrasound, to control the quality of blade manufacturing (Fig. 6.23).

With the development of the wind power industry, Chinese component manufacturers generally have established their own parts testing bench. The testing capacity of the platform is close to the advanced level of foreign countries, but there is still much room for improvement in terms of loading methods and data analysis methods.

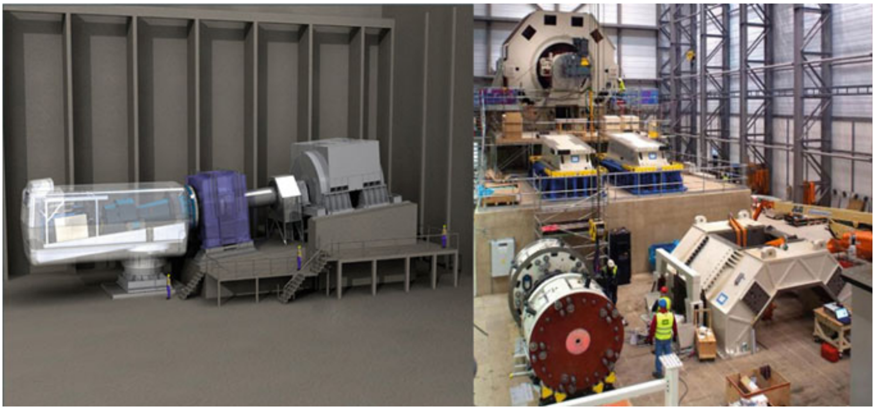

Fig. 6.22 New energy and renewable energy center 15 MW driving train test system

Fig. 6.23 National Wind Technology Center (NWTC) blade test device

6.4.4 Key Technologies of Wind Turbine Reliability Design

1. **Reliability Design and Evaluation Technologies of Wind Turbine**

With the continuous increase of wind turbine capacity and the update of wind turbine technology, the wind turbine design presents the development trend of large-scale, intelligent, and customized, and the wind turbine reliability design becomes more and more important. It is necessary to develop reliability modeling and analysis technology for wind turbine, study, and formulate relevant standards for wind power reliability modeling and reliability analysis, and establish a perfect reliability design evaluation system.

To research and build wind turbine reliability design evaluation system, it is necessary to study more refined modeling simulation technology, control system safety integrity evaluation technology, wind turbine and key components reliability target matching evaluation technology, and set up evaluation system of wind turbine reliability design suitable for the current technology trend, including product reliability design evaluation and reliability design tools.

2. **Reliability Data Collection and Analysis Technology of Wind Turbine**

At present, market demands for the evaluation of wind turbine operation quality are huge. However, there are no unified standards for the definition and calculation of wind turbine operation reliability. It is difficult to evaluate wind turbine operation reliability scientifically and effectively. Due to the complex operating environment of wind turbine, different wind conditions such as turbulence intensity, wind shear, inflow angle and different control strategies such as yaw and pitch, all of which will have a great impact on the performance of wind turbine. Various factors affecting the wind turbine performance need to be considered comprehensively to evaluate the difference between the actual performance and the design performance. As a result, the actual life and design life of wind turbine will often be big different. Therefore, it is necessary to establish evaluation method of residual life based on the models of actual wind turbine and the wind farms with actual environmental condition.

In order to solve the above problems, a unified calculation method for wind turbine operation reliability, a scientific calculation method for wind turbine generating performance, and an accurate evaluation method for wind turbine residual life should be established, based on reliability theory model, big data analysis technology, modeling simulation, and other technical means. Then, the reliability index analysis, power curve analysis, load, and structural strength analysis of wind turbine in actual operating environment can be carried out.

3. **Reliability Testing Technology for Wind Turbine**

The full-size ground test technology for wind turbines above 10 MW level, operation control technology of ground test system, and ground test technology of driving chain and key parts of large wind turbine, should be carried out. Especially under dynamic loading, a full-scale structural mechanics testing platform for 120-m wind turbine blades should be constructed, and a testing technology system for static testing, multi-degrees-of-freedom fatigue testing and damage assessment of superlong blades should be established. Relevant testing standards and methods also should be formulated. Technical requirements and criteria for blade safety verification testing should be put forward.

It is necessary to study the environmental adaptability and reliability testing technology of offshore wind turbines, improve the standard testing system of offshore wind turbines, master the whole life wind–wave coupling testing technology, and establish the offshore wind power test base.

6.4.5 Conclusion

With the continuous progress of wind power technology in China, further improvement in the reliability of wind power equipment has become the consensus of wind industry community. Some wind power equipment manufacturers have carried out related works to enhance domestic wind power equipment reliability, such as formulating reliability evaluation standard of wind turbine, analyzing the reliability data of wind power equipment in service, setting up the wind turbine and key components failure type list, etc., in order to lay a solid foundation for further development of reliability design and other related works in China.

However, there is still a big gap between China and other advanced countries in reliability modeling, reliability analyzing, and reliability testing of wind power equipment. For this reason, we put forward the following suggestions:

(1) Develop the Basic Research on Reliability Design

China has not yet deployed relevant projects in the basic research of reliability design of wind power equipment, such as collection and analysis of wind turbine operation data, reliability modeling and reliability design methods, etc. There are still many blank spaces in the relevant fields. Therefore, it is necessary to carry out in-depth research on reliability design methods and other related theories.

(2) Formulate the Relevant Standards for Reliability Design

It is essential to establish a set of corresponding technical standards of reliability design of wind power equipment, such as wind turbine and wind farm data coding, wind power equipment operation data collection, wind turbine reliability analysis, wind turbine reliability testing, and other aspects.

At present, many countries are also developing and improving reliability design standards for wind turbine. We can also formulate reliability design standards for wind power equipment suitable to China's national conditions, by making full use of international technology exchange and cooperation.

(3) Construct the reliability design simulation and testing platform

The reliability design simulation and test platform for wind turbine includes physical and numerical simulation test platform. At present, there is a big gap between China and foreign countries in the construction of reliability design platform for wind turbine. There is still no public test bench with advanced construction technology that can meet the needs of current and future upgrade of wind power equipment technology. In particular, the lack of driving chains and key components testing bench for large-capacity wind power units has become one of the bottlenecks restricting the sustainable development of wind industry, which needs to be solved as soon as possible.

(4) Implement the reliability monitoring

Reliability design of wind turbine is not simply a technical problem, but an important part of the quality management system of wind power. It requires supervision and management by the competent authorities concerned, especially the standardization, systematization, and transparency of data acquisition of wind turbines and wind farms, and the construction and utilization of public testing platform for wind turbines.

(B. Lv)

6.5 Design, Manufacture, and Maintenance of Large Wind Turbine Blades

With the continuous progress of the wind power technology, the single capacity of a wind turbine has also been enhanced from ten thousand watts at first to MW level and then even to tens megawatts. At present, the largest single capacity of wind turbine in the world has a rated power of 9 MW. However, due to the price pressure of traditional fossil energy and the competition within wind power industry, it is urgent for the wind power industry to upgrade the technology of large wind turbines, especially the large horizontal axis wind turbines. As the key component of wind turbines, the technologies in the design, manufacture, and maintenance of wind turbine blades are of vital importance for better operational performance.

According to GWEC, the amount of the global newly installed capacity exceeded 60 GW for the first time in 2015, and the cumulative installed capacity reached 432.9 GWs from 2000 to 2015. Asian installed capacity continues to lead the global market, followed by Europe and North America. Since 2009, China has been the largest market in the world. The newly installed capacity in 2015 and the cumulative installed capacity of China globally ranked the first.

Considering climate change requirements, wind power prices, and US market expectations, GWEC forecasts that the growth rate in the Asian market will remain more than 50% in the next five years, while the European market is steadily increasing and the North American market will grow strongly. By 2020, the total installed capacity in the world will reach 792.1 GW. It can be seen that the market of wind turbine blades still exhibits great potential for development.

With the global wind power market turning to the low-speed wind field and the offshore wind farm, the length of blades is growing. Figure 6.24 shows the development trend of single machine capacity and wind wheel diameter.

At present, the world's longest wind power blade is as long as 88.4 m (see Fig. 6.25), developed by the Danish LM and Adwen company and set up with 8 MW of offshore wind turbines. Among the wind turbine blades of 80 m and above, there are 83.5 m from the Danish SSP technology, the 81.6-m blades from German EUROS, and the 80-m blades designed and manufactured by Vestas. They will be used in the South Korea's Samsung 7 MW offshore wind turbines, Japanese MITSUBISHI's 7 MW offshore wind turbines and Vestas's 8 MW offshore wind turbines.

The longer blades are in the design stage. In terms of aerodynamic performance, the maximum power coefficient of the commercial wind turbine is over 0.5, which is designed by German Enercon Company by optimizing the blade geometry on the tip, and the blade root transition section as well as the cabin geometry. In terms of weight, the British Blade Dynamics Company produces a world's lightest 49-m

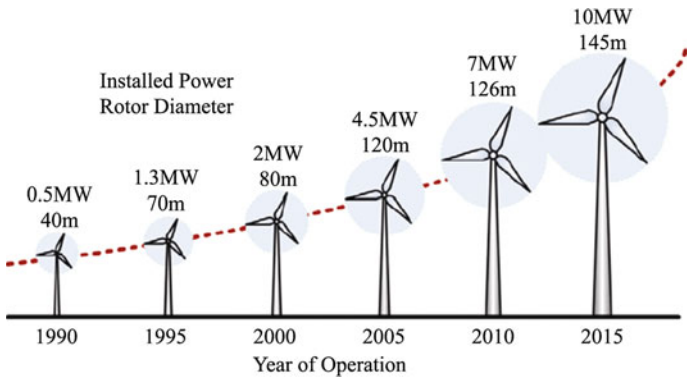

Fig. 6.24 Development trend of single unit capacity and wind wheel diameter of wind turbines

Fig. 6.25 LM's 88.4 long blades will be equipped with Adwen's 8 MW offshore wind turbine

blade certified by GL by using modular blade design and manufacturing technology. This kind of technology will be used for 100-m-long blade.

In the design and application of offshore wind turbine blades, SIEMENS has been in the forefront of the world, benefiting from the rapid development of the European offshore wind power market and its own technical advantages. The 58.5-m-blade with integrated blade design and manufacturing technology has been widely used for 3.6 MW offshore wind turbines. The 75-m blade developed with this technology will be produced and set up with SIEMENS 7 MW wind turbine, which will be installed on east coast of England. China's blade manufacturers are also closely following the step of international offshore wind power. At present, the blade of 6 MW wind turbine is 77.7 m of blade of SINOMA, 75 ms of blade of Zhongfu Lianzhong, and AEOLON's 75-m blade, but its design technology still depends on foreign blade design software such as WINDnovation and Aerodyn.

Owing to the demand of low-wind-speed field, blade design and manufacturing technology are advanced on a large scale in China. A number of domestic blade manufacturers rank in the forefront of the world. Jilin Chongton produced 2 MW wind power blade which has a length of 57 m. Other blade manufacturers have 50-m blade bulk products for 2 MW turbines. However, in the design of low-wind-speed blade, some manufacturers still rely on the foreign blade design technology to some extent.

In summary, China has provided the largest wind power market in the world at present. The domestic blade manufacturers have made great progresses in the design and manufacture technology of large-scale blades. Especially, the technology and application of low-wind-speed blades are in the forefront of the world.

6.5.1 Design of Wind Turbine Blades

With the augment of blade size, the Reynolds number, load and weight of the blade are increasing correspondingly, and the design of high efficiency, low load and light blade has become the goal of the blade manufacturers and research institutes. Therefore, some new airfoil, material, blade structure, manufacturing technology, and design method are continuously emerging and applied to engineering practice.

1. **Aerodynamic design of blades**

The objective of the blade aerodynamic design is to find the best blade profile, making the blade produce relatively smaller load while having higher wind power capture.

(1) Blade airfoil

Airfoil, as a basic element of blade aerodynamic design, plays a crucial role in the aerodynamic performance and load characteristics of the blade. Airfoils of early wind turbine blade were selected from aeroplane airfoil, such as NACA series airfoil. However, as people gradually realized the differences in the operating environment and flow field characteristics between wind turbines and aircraft, such as low Reynolds number, high flow turbulence intensity, multi-operating conditions and surface easy to pollute, they began to turn to develop dedicated airfoils for wind turbines.

The developed countries such as the USA, Denmark, Sweden, and Holland have carried out the research on the special airfoil for wind turbines and have made some achievements. They are the S series airfoils (Tangler 1995) proposed by NREL, FFA series airfoil (Bjork 1990) designed by the Swedish Institute of aviation, DU series airfoil designed by Holland Deft University (Timmer et al. 2003), Danish Riso series of airfoil developed by Danish National Laboratory (Fuglsang et al. 2004).

The maximum relative thickness of these airfoils is 53% (Bai et al. 2010), and it shows good performance on lift coefficient, lift drag ratio, roughness sensitivity, and stall characteristics. Among them, the DU series airfoil is widely used in the wind power industry. With the enhancement of wind turbine performance requirements and the deepening of understanding in the flow field characteristics, the development of the new airfoil is continuing.

In recent years, many domestic research institutes and universities are also developing special airfoil for wind turbines. For example, the CAS series airfoil developed by the Institute of Engineering Thermal Physics of the Chinese Academy of Sciences (Huang et al. 2013), the maximum relative thickness of the airfoil has reached 60%, and the design of the blunt trailing edge has a better structure and aerodynamic characteristics, which are important for improving aerodynamic performance near blade transition section (see Fig. 6.26).

The NPU WA series airfoil developed by Northwestern Polytechnic University (Qiao et al. 2012), the Reynolds number has reached 5×10^6, the airfoils has shown good aerodynamic characteristics, which is of great value for developing large-scale blades. The Shantou University introduced the noise requirements into the design of airfoils (Cheng et al. 2012) and obtained the low noise airfoil. In a word, the design

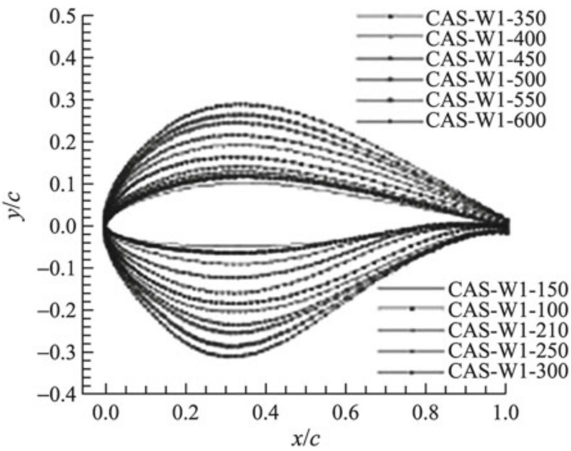

Fig. 6.26 Geometric shape of CAS W1 XXX airfoil family

of airfoils at high Reynolds number for large blade with better overall aerodynamic, structural and noise performance is the trend of future blade of wind turbines.

(2) Aerodynamic design method

In addition to the airfoil, the aerodynamic profile of the blade is mainly determined by airfoil parameters, such as chord length, twist angle, thickness, and the position of stacking axis. The aerodynamic profile of the blade has an important influence on maximum power coefficient, annual power generation, and the load of blades. Therefore, the aerodynamic design of the blade is a multi-variable and multi-objective problem. There are two main types of blade aerodynamic design methods, one is analytical method and the other is numerical method. The analytical method is mainly derived from the blade-element momentum theory simplified as BEM theory. Under the condition that the viscosity loss and the tip loss are not considered, the optimal aerodynamic shape of the blade can be obtained according to the BEM theory (Martin 2008):

$$\sigma_r \lambda_r C_l = \frac{4\lambda^2 \mu^2 a'}{\sqrt{(1-a)^2 + (\lambda\mu(1+a'))^2}} \tag{6.1}$$

$$a = \frac{1}{3}, a' = \frac{a(1-a)}{\lambda^2 \mu^2} \tag{6.2}$$

In the Formulae (6.1) and (6.2), σ_r is solidity, $\sigma_r = 3c/2\pi r$, λ_r for the local tip speed ratio, $\lambda_r = \Omega r / V$, C_l is the lift coefficient corresponding to the design angle of attack, λ for the design of the tip speed ratio, μ the spreading percentage $\mu = r / R$, and a as the axial induce factor, a' as the tangent induce factor.

With the Formulae (6.1) and (6.2), the chord length of each section can be calculated by selecting the design speed ratio and the lift coefficient of each section. According to the angle of attack corresponding to the lift coefficient and the angle of entry, the torsion angle of the section is calculated. The method is simple, it needs no iteration; therefore, the design speed is fast, which is suitable for initial design.

However, because it does not take into account the correlation between the chord length and the twist angle of each section, it is likely that the adjacent cross sections may not be over smooth and the workability of the process is poor. The numerical methods mainly include the direct problem method and the inverse problem method. In this design process by using direct problem method, initial distributions of blade chord length and twist angle as well as thickness are given, either from Formula (6.1) or based on the design experience. With the BEM method plus the modified model or the vortex method or the CFD method, such as Aerodyn, Bladed, FOCUS, FLUENT, and WT_ Perf, the analysis of blade aerodynamic performance is carried out. The design is automatically iterated through the manual iteration or the optimization algorithm to meet the design specifications.

In the automatic iterative method, the designer can restrict the chord length and twist angle of each section of the blade. It can set a single target or multi-targets for the design objective. Therefore, the aerodynamic shape of the design blade has excellent aerodynamic performances and a good process operability as well by using the automatic design code, such as the HARP_Opt software developed by the US renewable energy laboratory.

In addition, a new aerodynamic design method is proposed by Gunter to design higher-performance blade profile (2014). It mainly breaks through the limit of the standard airfoil, constantly modifying the cross-sectional airfoil during the optimization design by using the parameterized airfoil analysis via XFOIL software. In this way, the aerodynamic profile satisfying the design requirements is finally obtained through the iteration. The main drawback of this method is that the modified airfoils are difficult to evaluate its accuracy of aerodynamic performance data.

In regard to inverse problem design, only PROPID software is available, which is based on the development of BEM theory. The blade can be designed to meet the radial lift coefficient distribution and the axial inducer distribution defined by the designers. At present, the application is still limited. In general, the aerodynamic design of large-scale blades in the next few years will still be based on the direct method, especially on the optimal design method. For large-size blades, the significance of aerodynamic/structural coupling in the design appears more evident, and it will become a trend of blade design to optimize the aerodynamic and structural performances collaboratively.

(3) Aerodynamic analysis method

There are many aerodynamic analysis methods for large-scale blades. According to the different models, the aerodynamic analysis method can be divided into three categories: BEM method, vortex method and CFD Methods. The BEM method has the shortest computation time, and the computation of general blade performance takes only a few seconds. In the aerodynamic computation, the blade is dealt with several independent blade elements, and the calculation is easy to integrate with the structural dynamics analyze. Therefore, BEM is the most widely used method of aerodynamic performance calculation in current engineering design; BEM is also used by commercial wind turbine special software GH Bladed and FOCUS.

Of course, because of its large amount of simplification of the actual wind wheel model, there is a large error in the unsteady simulation and analysis of local aerodynamic performance. Therefore, in order to improve the accuracy of this method, some modified models combining theoretical derivation and empirical formula are constantly produced (Leishman et al. 1989).

The core idea of the vortex method is to simplify the distributed vortices in the three-dimensional flow field of wind turbine into a concentrated distribution of line vortices or surface vortices. Then, people calculate the aerodynamic performance of the wind turbine with the rigid tail vortex or the free tail vortex model. According to the simplified forms of the blade attachment vortices, it can be divided into the lift line model, the lift surface model, and the three-dimensional surface element model. Compared with the lift line model and the lift surface model, the three-dimensional surface element model does not need the two-dimensional experimental drag coefficient of the airfoil, and the calculation accuracy is higher. At the same time, it improves the computational efficiency of three-dimensional flow field as compared with the CFD model.

The Nanjing University of Aeronautics and Astronautics (Wang et al. 2009) used the predetermined vortex wake to determine the flow around the wind turbine, and introduced the vortex core structure and the dissipation effect caused by the viscosity to modify the model. Occurring when tip speed ratio is large, the divergence problem of vortex wake method can be resolved. The Institute of Thermal physics of the Chinese Academy of Sciences (Wang et al. 2012) combined the surface element model with the boundary layer model and the reduced order model to expand the ability of the surface element model to calculate viscosity flow. And the calculation accuracy of large separation flow is improved.

The CFD method has the highest precision in the three kinds of methods. People can obtain high-precision three-dimensional flow structure in detail around the blade. It is often used for aerodynamic performance evaluation, flow field analysis, and wake characteristics analysis of blades. This method has fewer assumptions and more advantages in unsteady flow analysis of blades. However, due to the multi-dimensional character of the wind turbine three-dimensional flow field, the unsteady and high turbulence characteristics of the wind field and the irregularity of the blade surface, the computation is both expensive and time-consuming. The operation is usually carried out on the parallel machine or supercomputers, which restricts its application in engineering design.

So far, some scholars have compared the above analysis methods, and found that their calculation results show nice consistency. However, due to the complexity of the unsteady aerodynamic characteristics of wind turbine flow field, the model used for BEM correction is often based on the approximate theory or the empirical correction formula, and its correctness is usually established under certain conditions, such as the dynamic stall model (Leishman et al. 1989). It needs to be further study and improvement to meet the demands suitable for large-scale development trend.

With the development of large and flexible blades, the problem of aeroelastic stability is highlighted again. How to avoid flutter and aeroelastic divergence in the design and development of blades will become an important scientific problem for aerodynamic design of wind turbine blades.

2. **Blade structure design**

The aim of the blade structural design is to find the optimal layer parameters of the blade material under the premise of maintaining the aerodynamic shape and structural reliability of the blade. The main challenge to the structure of large blades is that the proportion of the heavy torque in the blade increases sharply in the load—the instability of the edgewise direction structure becomes a prominent contradiction.

(1) Blade material

The material is the foundation in the design of the blade structure, and it is very important for the aerodynamic response characteristic and the structure performance of the blade. Wind turbine blade materials have been basically replaced by fiberglass composite materials when they have experienced times of wood, cloth, steel, and aluminum alloys. This is mainly because it has the following advantages: The strength and stiffness can be designed according to the load characteristics of the blade, the blade weight can be reduced to the utmost, the molding is easy, the notch sensitivity is low, the fatigue performance is good, and the internal damping is large. In addition, the material is easy to maintain along with better weather adaption.

The main materials used in the glass fiber composite blade include the following four categories: glass fiber, resin, binder, and core material. According to the stress characteristics and functional properties of each part of the blade, these materials are used in different position of the blade. In the meanwhile, the performance requirements of different materials are also emphasized differently. At present, the common glass fiber is E glass fiber. As the length of the blade increases, the requirement of the strength and modulus of the glass fiber becomes higher. So some more high-performance glass fibers have appeared, such as Saint Go in France; Bain group's H glass fiber; China SINOMA HS2 and HS4 high-strength silicon–aluminum–magnesium glass fiber; Chongqing Polycomp International Corporation's boron- and fluorine-free TM roving, and so on.

To further reduce the blade weight, carbon fibers are gradually applied to large-scale blades, such as 80 m of Vestas blade, 83.5 m of SSP blade, and 77.7 m of SINOMA blade. Studies have shown that the weight reduction of carbon fiber blades is more than 30% compared to that of glass fiber blades. This is mainly attributed to that the tensile modulus of carbon fiber-reinforced material is 2–3 times of the glass fiber-reinforced material, and its tensile strength is 1.12–1.44 times of the glass fiber, and it has high compressive strength, shear strength, and excellent damping characteristics. In addition, the conductivity of carbon fiber can avoid lightning. Its disadvantages are also apparent such as poor toughness, insufficient shape variables, poor wear resistance and skidding, high brittleness, high price, easy to be affected by technology (such as layer direction), poor wet ability, higher process requirements, poor transparency of finished products, and difficult to carry out Internal inspection.

In order to take advantage of high strength and high modulus of carbon fiber and control blade cost, carbon glass mixing technology has become an important research and application direction for large-scale blades. At present, there are two main ways; one is to lay carbon fiber in the main bearing position of the blade, such as spar cap, front, and back edge and so on, while glass fiber is still used in other places; one is to directly mix carbon fiber/glass fiber into one fabric and then lay and make it as a single material.

In recent years, carbon annotates (CNTs) with better performance have been paid attentions to by researchers and materials manufacturers. The related application research has begun. If the problem of aggregation of CNTs in resin can be solved well, the material has hope to become another important material for large-scale blades.

With the increasing demand for environmental protection, the disposal of waste blades has gradually become a serious problem. Most of the blades are made of polyester resin, vinyl ester, epoxy resin, and other thermosetting resin matrix. These blades are so difficult to burn or degrade as to occupy a lot of land. Research on low-cost, recyclable green composite materials has become an important research direction. Among them, thermoplastic composites have been widely concerned with by researchers and blade manufacturers. Compared to the thermosetting composite, it has the following advantages: It can be recycled; the molding process is simple and can be welded; the strength is higher; some mechanical properties are good, such as the specific stiffness, elongation, the permissible limit of failure, the good ductility, and the corrosion resistance, good corrosion, short curing period. The disadvantage is that the melt viscosity of the thermoplastic resin is high, the energy consumption of the process is high, and the fatigue resistance is poor. Therefore, seeking low melt viscosity and high mechanical properties of resin has become the research focus of thermoplastic composites.

In addition, research on biomass fiber materials has also been carried out and tried in blade production application. However, compared with FRP composites, this kind of material has poor comprehensive performance, such as low strength of bamboo composite blade, high cost of flax fiber blade manufacturing, and so further research and improvement is ongoing.

(2) Design method of blade structure

At present, large-scale blades are mainly composed of shell, spar cap, Web, reinforcement of blade root, enhancement of front and tail edge, and lightning protection system (see Fig. 6.27). Therefore, the structural design of blade is a reasonable arrangement of the main material based on the features of above different parts.

There are many factors to be taken into consideration in the design of blade structure, such as modal analysis, stiffness analysis, ultimate strength, and fatigue analysis. The modal analysis requires the natural frequency of the blade to avoid the resonant interval of the whole machine, and the stiffness analysis is mainly to control the deformation of the blade and meet the design requirements of the gap between the tip of blade and the tower. The ultimate strength analysis is performed to meet

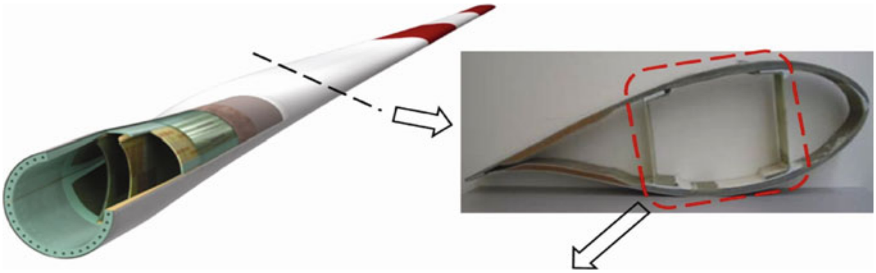

Fig. 6.27 Typical structure of composite wind turbine blades

the requirements of ultimate strength and buckling stability. The fatigue analysis is required for the service life of blade material more than 20 years or even longer.

With the progress of blade design technology, some structural properties that have been less concerned with have gradually become necessary design objectives in blade structure design, such as the ultimate strength analysis and fatigue strength analysis of structural adhesive, IFF analysis of matrix material, and nonlinear buckling analysis, the maneuverability of the layer process, and so on.

The development of large and flexible blades brings some new problems, such as the first-order torsion frequency of the blade is getting lower, thus leading to the blade aeroelastic divergence; the flutter stability boundary decreases gradually, even threatening the normal operation of the wind turbine. The analysis of the aerodynamic stability of the blade will be an indispensable step for the large blade structure design in the future. It is of great significance to improve the aerodynamic stability of the blade through structural design. It is also found that geometric nonlinearity of blades could affect the aeroelastic coupling characteristics of blades such as blade loads as well.

In short, in order to design better blades, the design objective should become more comprehensive. In the blade structural design, almost all problems are solved by the direct problem method. It is to use the engineering beam model or the finite element model (such as FOCUS, BModes, ANSYS, ABAQUS) to carry out the blade design, which is based on the design experience and the material characteristics. Each performance analysis, through the manual iteration or automatic iteration method, is carried out to meet the design objective of the blade layer information, including the location, thickness, angle, stacking order, and other parameters.

In automatic iterative analysis, intelligent optimization algorithms are often used (such as genetic algorithm and particle swarm optimization). Because of the variety of layer parameters and the flexibility of blade structure design, the method is often aimed at the large proportion of mass, such as the spar cap, the rear edge enhancement, and the blade root enhancement. Through the establishment of the parameterized model of the above parts and the corresponding blade performance analysis method, coupled with the optimization algorithm, the aim of optimizing the blade structure is finally achieved. This is also a kind of optimization design method of blade structure mentioned at present.

Because of some structure related performance analysis methods, such as the ultimate load calculation based on the standard load condition, it is not easy to establish the optimal design model, so the layer designed by this method needs to be further tested.

The optimization design method has low dependence on the designer's experience and fast calculation ability, which is suitable for the initial blade structural design. Manual iteration method can analyze every design objective in a comprehensive and detailed way, which is more suitable for detailed design of blade structure. At present, more and more researches on blade structure optimization design have been carried out (Liao et al. 2012). It has become a trend to design large-scale blades with optimized design models. But how to establish more accurate and efficient analysis model for structural design objective is the main point, such as the analysis of blade fatigue, the contact stress analysis of steel bushing and composite material, and the analysis of three-dimensional aeroelastic response.

The inverse problem design method is a more efficient design method, but because of many parameters involved in the design of blade structure, no one has put forward the design model. With the development of research, it may become a new way of large-scale blade design in the future.

(3) New type of blade structure

In order to better solve the problems caused by large-scale wind power generation, some new blade structures have been put forward, and some of them have been commercially applied. For example, the Blade Dynamics blade design company has proposed a modular design technique to reduce blade weight. It divides the blade shell into multi-block design and manufacture, and then reassembles it. The design of this type of 49-m-long blade has been completed. Xie (2015) proposed a foldable (folding) blade, which is divided into two segments, and the tip section of the blade can be folded to reduce the load.

For the sake of large-scale blade transportation, Enercon proposed a segmented blade, the blade root section is made of steel shell, and the tail flange plate is installed at the tail edge to ensure the aerodynamic shape of the blade root section. The tip section of the blade is composed of composite materials. Two parts of the blade are connected with bolt. At present, the blade has been produced and installed in batches. The static test (see Fig. 6.28) of a new sectional blade has also been completed in China, which is developed by the Institute of thermal physics of the Chinese Academy of Sciences and the Baoding Huayi wind turbine blade research and Development Co., Ltd.

It is necessary to monitor the running state of the blade and the blade load on line with the requirements for the reliability of the blade operation. At this moment, other strain measurement elements (Kim et al. 2011) are needed to be implanted in the blade for proposing new requirements for blade structural design. In addition, modular design and intelligent design have great application potential because of its advantages in weight reduction, convenient transportation, and better operation reliability.

Fig. 6.28 Static test of segmented blades

6.5.2 Manufacture of Wind Turbine Blades

The manufacturing technology of wind turbine blades is mainly based on the material system and three-dimensional geometric structure of blades. So far, there are mainly hand paste, molding, prepreg laying, pultrusion, filament winding, resin transfer molding (RTM), and vacuum infusion. These processes have their own advantages and disadvantages, which can be applied in accordance with the material system, geometric structure, geometry size, and layer function of the blade, so as to achieve the best effect.

Hand paste technology is a traditional process for producing composite wind turbine blades. Because it does not have to be affected by heating and pressure, and the cost is low, it can be used for manufacturing large and complex products at low cost. Its main disadvantages are low production efficiency, large fluctuation in product quality, and high reject rate. Hand paste process often accompanied by a large number of harmful substances and solvents release; there is a certain degree of environmental pollution. At present, it is mainly used for wet treatment of the leading and trailing edge after blade mold combining. The molding process has the advantages of high fiber content, low porosity, short production cycle, accurate dimensional tolerance and good surface shape. It is suitable for the production of simple composite goods. The disadvantage is that the input cost of mold is high and is not suitable for blades with complex geometry. At present, large-scale blades do not use this technology.

The main advantage of prepreg laying process is that the fiber-reinforced material is well arranged in the process of production and can make the components with low fiber defects and excellent performance. It is an ideal process for producing complex shape structure parts. Carbon fiber prepreg is widely used in aviation industry, and its main defect is high cost. Besides, the prepreg needs to be laid manually, and the production efficiency is low.

The pultrusion process has the advantages of high fiber content, stable quality, easy automation, and suitable for mass production. It is suitable for production with the same section shape and continuous molding products. However, due to the three-dimensional geometric bending and twisting structure of large-scale blades, the technology is seldom used.

Fiber winding process can control fiber tension, production speed and winding angle and other variables to make parts of different sizes and thickness. However, one of the defects applied to the blade production is that there is no winding in the longitudinal direction of the blade, and the lack of fiber in the direction of length makes the blade easy to cause problems under the load of high tension and bending. In addition, the rough outer surface produced by filament winding may affect the aerodynamic performance of the blade, and surface treatment must be carried out. Finally, core mold and computer control cost a lot.

Resin transfer molding (RTM) is a semi-mechanized composite molding process. The requirements for workers' technology and environment are far below the hand paste technology, and the quality of the products can be effectively controlled. The drawback of RTM is that the mold equipment is very expensive, and it is difficult to predict the flow of resin in the mold and cause defects easily. The RTM process adopts a closed mold forming process, which is especially suitable for the one molding whole wind turbine blade (fiber, sandwich, and joint can be formed in one mold cavity) without bonding.

Vacuum infusion molding is an ideal process for the manufacturing of large-scale blades. Compared with RTM, it saves time, has very little volatiles, simple process operation, and greatly reduced the cost of mold. Compared with the hand paste process, the tensile strength of the molded product is increased by more than 20%. In view of the advantages of the vacuum infusion molding technology in the application of large-scale blades, the large-scale blades are mainly produced by vacuum infusion technology.

In recent years, based on the vacuum infusion technology, the technological improvements are made in view of the thickness of the blade layer, the new high modulus material, the manufacturing efficiency, and the quality of the blade molding (Sainz 2015). At present, the innovative and practical representative blade manufacturing technology is: the IntegralBlades technology proposed by SIEMENS wind power group. It uses two mold surfaces and the core model to form a closed cavity with fiber and core material in the shape cavity. With the vacuum system built in the cavity, the matrix material is injected into the mold and the large-scale blades are formed at once. Compared with the traditional vacuum casting process, its advantages include: saving manpower and space, no need for bonding, high-quality reliability, no release of VOCs, and little environmental pollution. The technology has been widely used in the manufacture of different types of blades in SIEMENS.

Automatic blade manufacturing system developed by the DANOBAT Company. Its main functions include automatic spray coating, automatic spray short cutting, automatic laying, automatic polishing, automatic glue spreading, etc. Customers can choose overall automation according to their own needs, or choose one or more of them. The working unit adopts the movable cantilever beam structure, the cross-beam is installed with cross-slide rail, the corresponding working function head is located on the slide rail, and the 5-axis control is adopted. Finally, the automatic operation of each process is realized. Compared with the vacuum injection molding process, it has the advantages of high production efficiency; low labor cost, and good stability of blade quality (see Fig. 6.29).

In addition to the above manufacturing technology for the thermosetting composites, the production process for thermoplastic composites is developing. For example, the wet molding process based on low viscosity carrier technology and the cohybrid molding process (comingling): blending yarn (comingling yarn) with thermoplastic resin fiber and reinforced fiber. Resin fibers are melted and impregnated with reinforcing fibers during heating of blended yarns until all reinforcing fibers are thoroughly impregnated. These technologies can solve the problems of high energy consumption and poor fiber infiltration in thermoplastic composites to some extent. However, it is still necessary to further study the experiments to be applied to the actual manufacturing process of large blades.

To sum up, the large-scale blade molding process will develop in the direction of high molding quality, high production efficiency, low production cost, and low environmental pollution. Integrated and automated manufacturing technology, with its great advantages in forming quality and efficiency, will become a manufacturing trend for large-scale blades. At the same time, the manufacturing technology of thermoplastic composites has great potential for development. Among them, the development of low viscosity thermoplastic resin is very critical.

Fig. 6.29 Automatic blade manufacturing system

6.5.3 Maintenance of Wind Turbine Blades

In the development of the wind farm, whether the wind turbine can swing out the best performance during the rated operation period is one of the key factors to measure the success or failure of the wind farm investment. In addition to the quality of wind turbine, the operation and the maintenance in its life cycle is more critical. In 2015, the new installed capacity of China's wind power is about 30.5 GW, and the total installed capacity in 2020 will break through 200 GW. Such a huge installed capacity will make the wind turbine operation and maintenance market become a new growth point of the wind energy industry.

There are many differences between the offshore wind farm and the onshore wind farm, because of the high cost of logistics, operation and maintenance personnel maritime traffic and management of the port. The outage of the wind turbine and the failure of the large parts have double adverse effects on the operation and maintenance cost of the offshore wind farm. The maintenance of the large parts of the offshore wind farm is inconvenient, and the self-lifting barge is needed to be hoisted, which greatly increases the operation and maintenance costs.

As one of the key components of wind turbine, blade status directly affects the efficiency of wind turbine. Under the condition of high altitude and all weather, the blade often suffers from the invasion of air medium, atmospheric radiation, dust, thunderstorm, heavy rain and ice as well as snow, which can easily cause the damage of the blades.

It is not only time-consuming, but also ineffective to discover the potential problems and defects of the blades in time, which will exert great influences on the operation and maintenance of the wind turbine, and even cause an accident.

The defects produced during the production of wind power blades may be changed during the normal operation, resulting in quality problems. The most common defect is the tiny cracks on the blade (usually produced at the edge of the blade). The cause of the crack is mainly due to the defects in the process of production, such as delamination, which usually occurs in the incomplete areas of resin filling. Other defects include surface degumming, delamination in the spar cap area, and some pore structures in the material.

The advantage of wind power blade intelligent operation and maintenance system is to predict the operation status of wind turbine blades by integrating large data and evaluating the whole life cycle of wind power blades, and to maintain it in time to prevent failure, and help to realize the transformation of "fault maintenance" to "planned maintenance."

The intelligent operation and maintenance system of wind power blades makes use of the latest sensor detection, signal processing, large data analysis, and other techniques (Lee Jae Kyung et al. 2015; Kai Aizawa et al. 2014), real-time online/off-line monitoring of wind turbine blade operation. During the operation of wind turbines, the deterioration trend of wind turbine blade performance is automatically identified and maintenance strategy is formulated in time. The system should have the function of monitoring parameter setting, trend curve display, remote alarm, equipment fault diagnosis data summary analysis, and maintenance strategy formulation.

6.5.4 Concluding Remarks

Since 2000, the global wind power industry has been developing rapidly. With the improvement of people's awareness of environmental protection and the progress of wind power technology, the wind power industry will continue to maintain a high-speed development. Blade as the key component of the wind turbine, the development of its technology is of great significance for the whole wind power industry. In order to meet the requirements of large blade development, new airfoil, materials, design methods, and manufacturing technology are proposed continuously, thus leading to the progress in design and manufacturing technology of wind turbine blades and the production of high-performance blades. Generally speaking, large blades have the following development trends in aerodynamic design, structural design, manufacturing process, and operation and maintenance.

In aerodynamic design, the development of high-performance airfoil at high Reynolds number is an urgent problem to be solved. In addition, the development of high-precision and efficient aerodynamic analysis methods, especially for solving the unsteady aerodynamic characteristics of large blades, and the multidisciplinary coordinated design method will be an important research direction of wind turbine blades.

As for structural design, the development of blade materials with superior performance and environmental protection will be the focus of material research. On this basis, the optimization design technology and the inverse problem design method will be the main research trend. In addition, new type of blade structure for different problems appears, and modular design and intelligent design have great potential application because of their advantages in weight reduction, transportation, and improvement of operation reliability.

In the manufacturing process, the forming process with high molding quality, high production efficiency, low production cost, and low environmental pollution is the future development direction. Integrated and automated manufacturing technology, with its apparent advantages in forming quality and efficiency, will become a manufacturing trend for large blades. At the same time, the manufacturing technology of thermoplastic composites shows great potential for development. Among them, the development of low viscosity thermoplastic resin is very critical.

Intelligent operation and maintenance of wind turbine blades is the trend of wind power development at home and abroad. Especially in offshore wind farms, the high cost of operation and maintenance makes the development of intelligent operation and maintenance system become a top priority. At present, it is pressing to develop the technology of sensor detection, signal processing and large data analysis for large blade, so as to realize the transition from "fault maintenance" to "planned maintenance."

(X. L. Zhao)

6.6 Drive Train System Technologies for Large-Scale Wind Turbines

Wind energy has become the number one renewable energy in power supply with highest growth rate in three decades of development. The geographical location of the wind farms is experiencing the following transformations and expansions: from high-wind-speed fields to normal ones; from onshore to offshore; from coastal to distant; from developed countries to developing ones.

Subsequently, as the core part of the wind energy industry, the wind turbine is also evolving: upscaling of the unit capacity; expansion of the rotor diameter; efficiency of the generator—more permanent magnet synchronous generators are applied; optimization of the drive train system—direct-drive and medium-speed-drive are changed into preferable options.

The above circumstances are more evident for offshore wind turbine. Due to the harsh hardware requirements and the large amount of investment, the reliability and expense issues have gained more attention for large-scale wind turbines.

The drive train scheme is the dominant factor on system reliability and efficiency of energy conversion, researchers all over the world continues to design and test new strategies for the drive train system. To some extent, the improvement on the drive train system caused the transformation in the wind power technology since 1980s: from fixed-speed-fixed-pitch to variable-speed-constant-frequency; from speed step-up to direct-drive; from doubly fed induction generator (DFIG) to permanent magnet synchronous generator (PMSG); from high-speed-drive to medium/low-speed-drive; from distributed to centralized structure.

A wind turbine consists of mechanical and electrical parts. The mechanical part includes: main shaft system (main shaft, bearing, bearing block), coupling, gearbox, high-speed shaft (mechanical brake and coupling are included), and rotor of the generator; the electrical part contains the generator and converter system.

The drive train system brings about tremendous impacts on the cost for investment in wind energy: The expense of the drive train can take up as high as 40% of the whole wind turbine cost, overweight problem would result in higher expense in tower part when upscaling the unit capacity; the efficiency of the drive train system would shift the electrical power generation capability and possibly leave a more demanding task for the cooling systems; maintenance cost and power generation loss is going to be problematic once the wind turbine has to be shut off. Reliability, weight, and efficiency are the benchmarks for evaluating a drive train system, especially for offshore wind turbine. The drive train for modern wind turbine is summarized in Table 6.4.

Table 6.4 Drive train system for modern wind turbine generators

Drive train system						
	Type	Speed	Transmission	Method	Generator	Converter
Rotor	Geared	High	Three/Four-stage	Gearbox	DFIG	Partial scale
					SG with exciter	Full scale
		Medium	Single-stage (Multibrid)		PMSG	
			Two-stage (Vestas)			
			Multi-output (Clipper)			
	Gearless	Low				
					SG with exciter	
					Superconducting	
	Other		Differential	Hydraulic (Voith)	SG	
				Electromechanical		
			Stepless	Gearbox		
			Hydraulic			

6.6.1 Present Status of Drive Train Technologies

1. **Worldwide**

Europe and USA lead in new drive train technology research and applications. Wind energy is fully industrialized in Germany, Denmark, and USA, which includes research, components support, manufacturing, and exploitation of the wind farm; similar situation can be found in Spain; Research, design, and consulting are generally the leading business in Netherlands and UK; key components manufacturing are very competitive in France, Sweden, and Finland. High-speed-doubly fed and direct-drive are two state-of-the-art strategies for the drive train of the commercialized main stream wind turbine. Medium-speed-drive technology has been the most promising scheme over the past few years and gained more attention internationally.

High-speed-doubly fed

During the early years of wind energy industry, the components suppliers were only "part-time," they were not dedicated to wind energy industry. Therefore, the manufacturer of the wind turbine had to select more general components (such as main shaft, bearing, gearbox, and generator) for designing, which led to the distributed structure. It became more prevalent after the emergence of Danish wind turbine in 1980s. The drive train scheme for high-speed-doubly fed type wind turbine was evolved based on it when variable-speed-constant-frequency started to be popular for MW-level models: The generator was simply replaced with DFIG, partial-scale converter was added, and the rest of the system was "upscaled." For hundred-kW, MW-level and multi-MW-level wind turbine, three/four-point are the most common support structures, the generator is located behind the gearbox and connected with it using the high-speed shaft.

High-speed-doubly fed has become a fully developed technology; it plays an important role in industrialization of wind energy all over the world with abundant sources of supply and relatively low cost. Majority of the drive train schemes from the world's top manufacturers is high-speed-doubly fed, it held over 90% market share for newly installed wind turbine as of 2008. However, this number dropped to 75% as of 2016 due to the competition with other drive train strategies.

The largest unity capacity for large-scale wind turbine using high-speed-doubly fed scheme is 6 MW. Although the manufacturers have been trying to improve the key components such as high-speed gearbox, electromechanical pitch system and DFIG, the reliability remains a problem as unit capacity upscaling undergoes. Therefore, high-speed-doubly fed scheme is gradually abandoned for wind turbines.

For onshore wind turbine, the manufacturers continue with high-speed-doubly fed scheme by optimizing generators' integration capability to accommodate the current grid regulations. Some of the manufacturers have already replaced DFIG with high-speed PMSG, which helped form the high-speed permanent magnet drive train scheme.

Direct-drive

Enercon from German has been concentrating on direct-drive technology while majority of the manufacturers were following high-speed-doubly fed strategy. The unit capacity was increased to 7.5 MW starting from 330 kW back in 1991. Enercon stayed among the leading manufactures in installed capacity for over a decade in German, and world's top 10 manufactures due to its high reliability advantage, even with higher cost. Nevertheless, synchronous generator with its excitation system has more complicated structure, higher weight and is less economically attractive, which prevents direct-drive scheme to become the first option for large-scale wind turbine. The market strategy for Enercon is prioritizing its onshore product lines, the 7.5 MW series still could not be applied to offshore projects even if the onshore prototype has been under operation for years.

Starting from around year 2000, the technological transformation trend for wind turbine was generally from fixed-speed to variable-speed, fixed pitch to variable pitch, kW level to MW level and geared to gearless transmission, more manufacturers and research facilities have joined Enercon to improve the direct-drive scheme.

Vensys from Germany applied PMSG to direct-drive wind turbine; its 1.5 MW model was successfully brought to the market and further to the field for service through Goldwind from China. This made the direct-drive permanent magnet technology another mainstream drive train scheme after high-speed-doubly fed. Siemens from German has already designed and developed its 6 and 8 MW models for offshore projects based on the 3 MW direct-drive PMSG model.

Medium-speed-drive

Design company Aerodyn from German has pioneered the medium-speed-drive wind turbine and focused on the research and development of medium-speed-drive scheme along with its regular high-speed-doubly fed technology. The Multibrid 5 MW model has been applied to multiple offshore projects in UK, Germany, and France. During year 2001–2005, National Renewable Energy Laboratory (NREL) from USA initiated the WindPACK project and contracted two independent teams to study the economical characteristics of high-speed-doubly fed, direct-drive permanent magnet, and medium-speed-drive technologies. The two teams all concluded that the medium-speed-drive scheme has the lowest cost and is economically promising among the three technologies. Consulting company Garrad Hassan (GH) from UK provided similar conclusion later on. Two teams from Vestas used direct-drive and medium-speed-drive, respectively, when developing the V164 offshore wind turbine. The medium-speed-drive plan was selected afterward due to its less expense to create the largest unit capacity (9.5 MW) model as of 2017. Gamesa from Spain started research and development of its 4.2 MW series product in 2007, and the medium-speed-drive scheme was used for the model, which continued to be the case for AD 8 MW model by its offshore wind turbine manufacturing company Adwen jointly funded with Areve from France. AD 8 MW series has the largest rotor diameter at 180 m among its peer models.

Other technologies

Converter system became an essential part of the wind turbine as variable-speed-constant-frequency model is widely accepted. Due to the bottleneck of the power electronics per se, the reliability of the whole generation unit is substantially affected (error rate and downtime can go up to 20%), even more than the gearbox. An alternative plan is investigated regulating the speed at the mechanical input end of the generator, in which way the converter system can be eliminated entirely. This technology requires a set of speed regulation equipment in between the gearbox and the generator; it can be either mechanical (continuously variable transmission) or hydrodynamic (hydraulic coupling). AC output end can be connected to the step-up transformer directly. There are two schemes to achieve speed regulation: (1) hydraulic drive train system; the gearbox is fully replaced, speed step-up and regulation are both accomplished through hydraulic transmission; (2) hybrid hydraulic drive train system; hydraulic drive train system and the gearbox are integrated together. The two schemes haven't been applied in industrial projects and still stay in research and test stage after 30 years of development.

A further application based on hydraulic transmission is to take advantage of the fluid in long-distance transmission, the hydraulic pump and the following equipment can be relocated to the ground level of the tower, which is convenient for maintenance. For the offshore wind turbine, the seawater pump is driven by the hydraulic motor to create energy input for the hydraulic turbine at the far end; the electric power is then transmitted to onshore station. Jet Propulsion Laboratory (JPL) from USA proposed a scheme for long-distance hydraulic transmission in 2012, which used the hydraulic pump in nacelle and hydraulic pump at the far end for the synchronous generator. The generator for offshore projects can be located either onshore or on the offshore platform; for onshore wind farm, the top level pump of each wind power generator can be connected to a high-pressure joint duct system to the far end generator, the returning fluid can also be led to a joint duct system for the hydraulic pump of each generator. A 15 MW test system was created for simulation studies, components, efficiency, and economy evaluations.

2. **Domestic**

Manufacture of wind turbines in China is generally licensed production based on European technologies, or simple upgrade and follow-up design. The overall research and development are not as competitive as the international leading facilities, which is currently in follow-up stage to gain more experience through testing platforms for key components (such as gearbox and generator). The prevalent strategies are also high-speed-doubly fed, direct-drive and medium-speed-drive.

High-speed-doubly fed

Around 70% of the manufactures selected high-speed-doubly fed scheme since 2005 when wind power energy industrialization started in China. Since the technology was imported from Europe, the early applications had run into problems that brought impacts to the reliability of the generators. The posterior improvements have eased such situations and currently high-speed-doubly fed is the primary scheme.

Direct-drive

Goldwind from Xinjiang started to import direct-drive technologies back in 2003 for manufacturing PMSG-based direct-drive wind turbine. Beginning from 1.2 MW prototype, 1.5 and 2.5 MW products are currently available in the market, and the 6 MW prototype is under research and development. Xiangdian and Yinhe also imported the 2.0 and 2.5 MW direct-drive permanent magnet technologies respectively in 2005, the resultant 2.0, 2.5, and 5.0 MW PMSG-based direct-drive wind turbines were then manufactured. Different from Goldwind, where the rotor of PMSG is outside the stator, PMSG rotor is inside the stator for Xiangdian.

Medium-speed-drive

As the industrialization of wind energy has been moving steadily since domestic manufacturer started to investigate different drive train schemes. Goldwind proposed the medium-speed-drive (semi-direct-drive) scheme for National Technical Support Program, then designed, and manufactured the 3.0 MW model individually. The prototype was integrated into the network in 2009 and has been successfully under operation for over 7 years. The second-generation prototype was ready for test.

Mingyang imported the SCD double-blade compact-medium-speed-drive technology from German's Aerodyn in 2008. Due to the lower wind power capturing ability, power generation capability of the prototype was undesirable. The improved 3.0 MW onshore and 6.0 MW offshore models were then designed and manufactured to stay in the wind power business.

Beijing Tri-power New Energy (TPNE) Science and Technology Co., Ltd. was founded in 2012, the medium-speed-drive onshore and offshore models are its primary products. Based on the market demand for low-wind-speed regions (6 m/s and lower, annual average), TPNE has individually developed the 2.0 MW medium-speed-drive wind turbine with 122/130 m rotor diameter. The applied high-reliability medium-speed-drive scheme and hydraulic pitch control system coincided with the offshore applications V-164 by Vestas and AD-180 by Adwen. The design swiftly drew attentions from the industry, the first medium-speed technology symposium was held in March 2017, and the design was recognized and highly rated among the peers.

Another technology worth mentioning is the so-called high-speed permanent scheme, which is considered as the replacement for high-speed-doubly fed internationally. The scheme is a flexible alternative to accommodate the low-voltage-ride-through requirement based on the original high-speed-doubly fed model. When the requirement became mandatory, DFIG manufacturers like Vestas attempted to replace the induction generator and partial-scale converters with permanent magnet generator with full-scale converters based on the DFIG's original arrangement. However, the scheme is not technically a new technique, but an expedient.

Other technologies

The hydraulic drive train system has been studied in Lanzhou Institute of Tech. The original drive train of a 600 kW DFIG was modified. The fixed displacement pump was used to replace the gearbox and generator. The hydraulic pump was directly driven by the rotor to transmit the high-pressure fluid to the variable displacement hydraulic motor on the ground. The motor then served as the prime mover for the synchronous generator.

Trend of drive train technologies

Low cost is what the wind energy industry has always been pursuing for both onshore and offshore products, especially for offshore ones. European Union (EU) and USA have all initiated research and development projects on 10 MW and larger models, which all includes dedicated studies on the drive train system, such as Upwind and Inwind projects from EU, and the Next-Generation-Drive train (NGD) projects from US Department of Energy. The workshop of "Advanced Wind Turbine Drive train Concepts" was held in USA in 2010. The next-generation drive train technologies were evaluated during the workshop, the objective is to improve the reliability, operation performance and cost of the wind turbine drive train. Superconducting generator/advanced permanent magnet generator, continuously variable transmission drive train, fluid drive train and novel/non-conventional drive train are the four principal research topics.

Technical University of Denmark (DTU) collaborated with Vestas to develop a 10 MW prototype using medium-speed-drive technology in 2015. The main research objective is to study the aerodynamics, aeroelastics, and structure design for super-long blade, which is then applied to reduce the vane weight as much as possible.

Based on this 10 MW prototype by DTU, the EU founded a cooperative research program Inwind that involved 29 organizations from the industry, research facilities, universities, etc. It was targeted to innovate technologies for offshore wind turbine, which can be applied to 50 m and deeper coastal areas with lower cost.

The program content included research and verification of 10–20 MW offshore wind turbine and the associate key components; next-generation subsystems and generation unit design evaluation system. As for the new drive train schemes, research on components for new type direct-drive generator. Especially for direct-drive drive train, superconducting generator and sub-direct-drive generator were proposed to replace the current conventional permanent magnet generator. Superconducting generator used MgB_2 and RBa_2Cu_3O (or RBCO) as the wiring material. MgB_2 is considered to be the most achievable scheme; RBCO is more costly, but it is believed to be the most economical option in the foreseeable future. The magnetic gear technology is one possible solution for sub-direct-drive generator, where the gear and the generator are both combination of mechanical and electromagnetic objects.

US department of energy founded NREL for research and development of the next-generation drive train scheme for 10 MW-level wind turbine based on the need for offshore projects. The primary plans from NREL are direct-drive scheme based on superconducting generator and medium-speed-drive scheme based on medium-speed gearbox.

Low cost represents the most important goal for the onshore wind turbine investors due to the limited wind energy and land resources. As the related fields for the wind energy industry start to catch up, the unit capacity of the generator continues to grow and the current mainstream products are rated at 3.0–4.0 MW level. However, the manufacturers are still pursuing the conventional drive train schemes: the high-speed permanent magnet scheme for Vestas 3.45–4.2 MW models; direct-drive permanent magnet and high-speed synchronous generator schemes for Siemens 3.2–3.6 MW models; high-speed-doubly fed scheme for GE 3.2–3.8 and 4.8 MW models; direct-drive-exciter scheme for Enercon 3.0–4.2 MW models.

6.6.2 Medium-Speed-Drive Technology

1. **Technical roadmap of medium-speed-drive**

Concept of medium-speed-drive

German wind turbine design company aerodyn Energiesysteme GmbH pioneered the innovative medium-speed-drive technology. They applied for a patent on single-stage planetary gearing and permanent magnet generator combination, and multiple schemes were proposed for implementation. One of the schemes was to use only one main shaft, which was integrated in the gearbox using three arrays of cylindrical roller bearings as shown in Fig. 6.30. The scheme shared the same design concept with the Winwind 1 MW model. In year 2003, they applied for another patent on single bearing with inner ring gear as prime mover. Single-stage, two-stage planetary gearing and using coupler between gearbox and generator were proposed for implementation, the scheme shared the same design concept with the Multibrid 5 MW model.

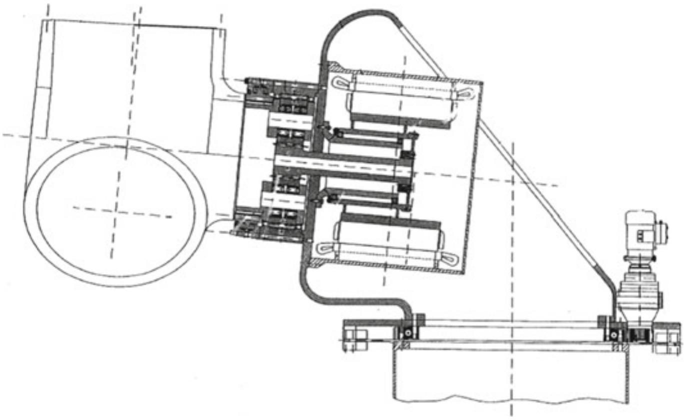

Fig. 6.30 Mono-main-shaft scheme

NREL from USA contracted Global Energy Concepts, LLC (GEC) for a systematic study on drive train of the wind turbine during 2000–2002, which included: alternative schemes for the drive train system, efficiency of the drive train, power generation capability, cost of components, initial investment on the wind farm, expense for operation and maintenance. The conclusion was that medium-speed-drive scheme would lead to the lowest cost compared to direct-drive and high-speed-doubly fed schemes. GEC started to design and manufacture 1.5 MW prototype model using medium-speed-drive scheme in 2002, and the design concept of the drive train system is displayed in Fig. 6.30.

Conceptual model by GEC (single-stage planetary + PMSG)
Northern Power Systems (NPS) also conducted a similar study on the drive train system from the end of 2001 to the beginning of 2005 according to a contract with NREL. The conclusion was that there was basically no substantial difference on the total cost between direct-drive and high-speed-doubly fed schemes, medium-speed-drive scheme had the lowest cost. The conclusion from NPS agreed with the one from GEC, and this partially set the foundation for further research and development work on medium-speed-drive scheme.

Research and development with medium-speed-drive scheme
The medium-speed-drive scheme was applied in research and development of wind turbine around year 2010. Aerodyn had initiated the development of Winwind 1, 3 MW and Multibrid 5 MW models beforehand. During that time, Gamesa also started to work on 4.5 MW model using medium-speed-drive scheme, which triggered the research and development with medium-speed-drive scheme among the mainstream wind turbine and components manufactures. GE, Vestas, and Siemens all applied for patents on models using medium-speed-drive scheme, respectively. The resultant V164-8 MW model and the V164-9.5 MW model (largest unit capacity as of now) based on Vestas patent are illustrated in Fig. 6.31.

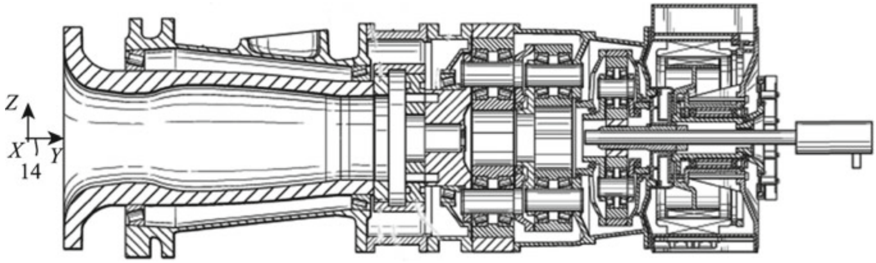

Fig. 6.31 Implementation of Vestas medium-speed-drive technology

Aerodyn applied for a patent on a wind turbine model using medium-speed-drive scheme in 2010. The patent was then applied in SCD 3.0 MW and SCD 6.0/6.5 MW models (Fig. 6.32). Clipper and Samsung had done research and development works on 10 and 7 MW models using medium-speed-drive scheme, respectively (Fig. 6.32).

For domestic manufactures, Goldwind and Huaren had done research and development works on 3 and 3.6 MW models using medium-speed-drive scheme, respectively, but they were not ready for mass production. The 3.0 MW model by Mingyang has already been deployed for service in the wind farms. Starting from the establishment of the company in year 2012, Beijing Tri-power New Energy Science and Technology Co., Ltd. has always treated the medium-speed-drive model as its main product. The research and development of 2.0 and 3.0 MW models has been completed, and the 2.0 MW model is now in mass production stage. Currently, the company is working on the 8.0 MW medium-speed-drive model for offshore projects.

2. **Typical medium-speed-drive applications**

Winwind

Winwind from Finland has obtained the right to use Aerodyn's patent on medium-speed scheme, and it had finished the design of WWD 1 MW model via collaboration

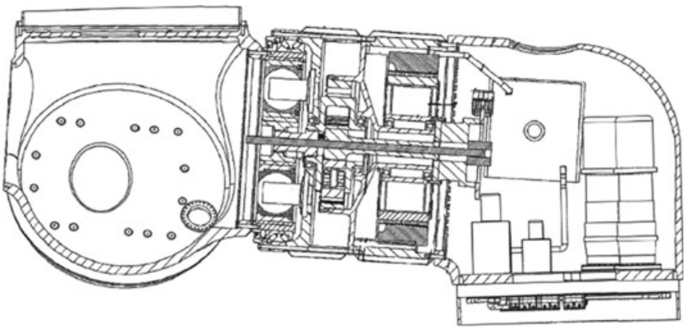

Fig. 6.32 Drive train system application for SCD

with Aerodyn and Moventas (gearbox). The prototype was installed in Oulu Finland in summer 2001.

WWD 1 MW model is a complete implementation of Aerodyn's original design, it corresponds the concept medium-speed-drive. Winwind had gained enough experience to start its 3 MW model design after the installation of 10 more WWD 1 MW wind turbines. The prototype of 3 MW model was installed in November 2004 right next to the 1 MW model.

The CTO of Winwind explained the reason for applying the medium-speed-scheme in 2003 European Wind Energy Conference: The direct-drive scheme makes the wind turbine too heavy. The high cost makes it difficult to compete with the conventional models. The only means to fill the gap is using large-scale equipment and the finest manufacturing crafting, and this barely set the direct-drive model suitable for industrialization. The reliability of generator in a direct-drive model differs from the traditional ones; overwhelmingly large geometric structure could cause detailed problems: inconsistent air gap due to heated expansion and enforced deformation; impacts from salty, humid and eroding air; transportation and installation of sectionalized stator. Most of the gearbox incidents happen in the sensitive high-speed level, the low-speed level is more reliable. It is risky to pertain the low-speed level; this can be made up by improving the design of the model.

The main differences between drive train system of the WWD 3 MW model and WWD 1 MW model are as follows: Two-stage planetary gearbox was used instead; large-size twin arrays of conoid roller bearings was applied for the main shaft, the gearbox and the generator no longer shared the same housing, the shape of the generator became slender and it was fixed at the base via gearbox flange after being installed together with the gearbox, the design is shown in Fig. 6.33.

Multibrid

Pfleiderer Wind Energy GmbH also purchased Aerodyn's medium-speed-drive patent. They developed the "Multibrid" 1.5 MW model in association with Aerodyn and WindTec Gmbh (originally from Austria, now is a subsidiary of AMSC), the prototype was installed in October 2001 in Zurndorf, Austria. The company started to design the Multibrid 5 MW model (aka M5000) after the success of its 1 MW

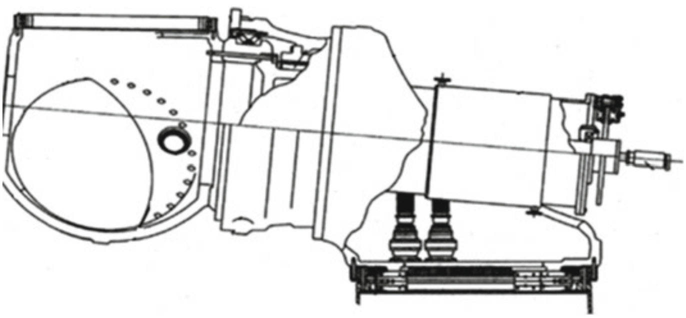

Fig. 6.33 WWD 3 MW model (two-stage planetary + PMSG)

model, during which Multibrid became a registered subsidiary of Pfleiderer. The installation M5000 prototype finished on December 2, 2004, in Bremen, Germany; the grid integration succeeded on 22nd of the same month. The second M5000 was installed on December 11, 2006, on the beach tripod; the wind turbine then had already had all the features for offshore application.

Multibrid 5 MW model used twin arrays of conoid roller bearings for the main shaft, compound planetary gear was driven by the ring gear, and the permanent magnet generator obtained the torque from the sun gear. Gearbox, generator, and the base shared the same housing. Strictly speaking, the planetary gearing was a two-stage distributary parallel axes transmission.

Multibrid was acquired by French manufacturer Areva in 2010, and 120 wind turbine was then installed for offshore projects in 2015, which makes Multibrid 5 MW the most installed medium-speed-drive model.

Gamesa/Adwen

Dual-shaft system, two-stage planetary gearbox and PMSG were used for the drive train system of Gamesa G128-4.5/5.0 model. Distinctly, the rotor was supported by independent main shaft; the gearbox and generator were all behind the main shaft. Models based on Aerodyn technology all placed part of the whole gearbox and generator section in between the rotor and base.

G128-4.5 prototype was installed in 2008 in Alava Spain. Due to the relatively smaller scale for offshore application and lack of offshore wind farm in Spain, the number of installed Gamesa 4.5/5.0 as of March 2017 is approximately 40.

Adwen was a joint venture of Gamesa and Areva starting from March 2015, the wind power section of Siemens merged with Gamesa in June 2016 and Adwen became a subsidiary fully owned by Gamesa in September 2016. Adwen currently has three products for offshore application: AD 5-135, AD5-132, and AD 8-180. AD8-180 is a 7 MW model using Gamesa's drive train scheme: dual-shaft system, two-stage planetary gearbox, and PMSG were behind the main shaft. Different from Gamesa 4.5/5.0, the connection of generator and gearbox was more compact, the voltage level of the generator was changed from low-level into medium-level. AD8-180 model has the world's largest rotor diameter as of August 2017. AD 5-135 and AD 8-180 are the major models for Adwen, as of March 2017, the intent order had gone up to 1800 MW (1500 MW was from AD 8-180).

Vestas

V164 7 MW model for offshore projects by Vestas had similar drive train arrangement to AD8-180 mode, dual-shaft system, two-stage planetary gearbox and medium-voltage-level PMSG were behind the main shaft.

Based on V164 7 MW model, the 8 MW model was then developed in 2013, the prototype started to run in January 2014 in Denmark. In 2017, Vestas upgraded the model to 9 and 9.5 MW, latter is the world's largest unit capacity so far. V164 had already had its first offshore application with 32 units running steadily. As of March 2017, the ordered capacity had surpassed 1940 MW, which would be installed within 3 years.

Table 6.5 summarizes the drive train parameters of medium-speed-drive wind turbine by various manufacturers. It can be seen that there are two types of rotor support: One of them is using dual-shaft system, independent from the gearbox, generator, and gearbox are placed behind the main shaft; the other one is Aerodyn style; main shaft is integrated in the gearbox, main shaft, gearbox, and generator are in between the rotor and base. The dual-shaft scheme is able to help the gearbox endure only the mechanical torque to lower the risk for it.

Table 6.5 also provides the gearbox stage level and ratio, a gearbox ratio at 40 is simpler to be obtained via two-stage drive train system, which is also the optimum ratio (economic-wise) considering the gearbox and generator costs. The medium voltage level is preferable for the PMSG of large-scale models.

Domestic application

The prototype of Goldwind's 3 MW medium-speed-drive model was installed in 2009 in Jiangsu; there are 10 units under operation as of now. 1 is in Xiangshui, Jiangsu, 2 of them are in Liuyuan, Gansu, and the remaining 7 are all in Dabancheng, Xinjiang.

The 3.6 MW medium-speed-drive model designed by Huaren has been manufactured by Huachuang, and more than 10 units were exported to USA.

Table 6.5 Drive train system parameters of medium-speed-drive wind turbine generator

Model	Designer	Installed time	Rotor support	Gearbox type	Gearbox ratio	Voltage level
WWD1	Aerodyn	2001.9	Integrated in gearbox	Single-stage planetary	7	Low
WWD-3	Aerodyn	2004.11	Integrated in gearbox	Two-stage planetary	29/39	Low
M5000	Aerodyn	2004.12	Integrated in gearbox	Two-stage sub-planetary	9.8	Medium
SCD3.0	Aerodyn	2010.8	Integrated in gearbox	Two-stage planetary	23.94/25.34	Low
SCD6.5	Aerodyn	2015.3	Integrated in gearbox	Two-stage planetary		Low
G128/132	Gamesa	2008.12	Independent twin-shaft	Two-stage planetary	37.88	Low
GWH3.0	Goldwind	2009.12	Independent	Two-stage planetary	25/38	Low
V164-8/9	Vestas	2014.1	Twin-shaft	Differential two-stage planetary	38.3	Medium
TP2.0	Tri-power	2015.10	Independent	Two-stage planetary	38	Low
AD 8-180	Adwen	2017 (planned)	Twin-shaft	Two-stage planetary	41	Medium

The prototype of SCD 3.0 model by Mingyang was installed in August 2010. As of March 2017, 50 MW had been installed in the field and 50 MW more were undergoing, there are 70 MW intent orders.

3. **Applications of medium-speed-drive wind turbines**

The availability of a wind turbine is an overall indicator based on maintainability and inherent reliability. For onshore wind turbine, great maintainability is beneficial for improving the availability; the requirement for inherent reliability is relatively moderate. On the contrary, great maintainability is not equal to better availability for offshore wind turbine, improving the inherent reliability is the primary mean to achieve better availability. Direct-drive and medium-speed-drive models both have greater inherent reliability, which is the reason why they are more common drive train schemes for offshore wind turbine.

Table 6.6 displays the installed capacity for 5 MW and larger models; it can be seen that the only model that used high-speed-doubly fed technology is Repower 5/6 by Repower. Based on the installed capacity for different drive train schemes shown in Table 6.7, the medium-speed models have gained higher grow rate for the past several years, and the cumulative installed capacity have already surpassed the doubly fed models. The medium-speed scheme becomes the preferred option for large-scale offshore wind turbine. For either offshore or onshore projects, the dominant factor for higher profit-investment-ratio is lower cost. The primary reason for applying medium-speed scheme in offshore projects is low cost, which is also suitable for onshore projects with low annual average wind speed.

Table 6.6 Installed capacity for 5 MW and larger models (as of 2017.03)

≥5 MW model	Drive train scheme	Initial installed time	Cumulative capacity (MW)	Capacity in last three years (MW)
Repower 5/6	Doubly fed	2004.10	1019	402
M5000	Medium-speed	2004.12	640	600
G128/132-5	Medium-speed	2008.12	164	46
GE/Alstom-6	Direct-drive	2012.8	42	30
SWT-6/7	Direct-drive	2012.10	241	223
V164-8/9	Medium-speed	2014.1	258	258
XE128-5	Direct-drive	2015.11	50	50

Table 6.7 Installed capacity for different drive train schemes

Drive train scheme	Cumulative capacity (MW)	Capacity in last three years (MW)
Doubly fed	1019	402
Direct-drive	333	303
Medium-speed	1062	904

Electric power generation capability for medium-speed-drive models is comparable to direct-drive models. For low-wind-speed and superlow-wind-speed conditions, the medium-speed-drive models have nearly zero generation loss compared with direct-drive ones; the cost for medium-speed-drive models are lower than direct-drive models, which is comparable to doubly fed models; the reliability is higher for medium-speed-drive models and the follow-up operation and maintenance cost is lower than the doubly fed models. For low-wind-speed and superlow-wind-speed regions, the medium-speed-drive wind turbine has the lowest cost during its lifetime.

6.6.3 Critical Technologies for Medium-Speed-Drive Scheme

Medium-speed-drive is a new type of drive train technology; the widely accepted definition of it is a drive train system that contains single-stage or two-stage planetary gearing. The gearbox, generator, and converter are the three primary study objects for medium-speed-drive technology, where the gearbox is the major one. The ultimate goal is to optimize the medium-speed-drive train based on its reliability, efficiency and cost, and lower the cost. The critical technologies that require further studies to achieve the goal are given as follows:

Study on drive train scheme
If conventional planetary drive train scheme is used for superlarge-capacity high-torque gearbox, the size of which would be beyond the capability of existing manufacturing industry. Nevertheless, the precision can be extremely difficult to control (or guarantee). New drive train scheme should be considered such as multi-planetary-wheel and compound-planetary- distributary to lessen the size and weight and increase the power density.

Study on average load based on large-capacity-high-torque drive train
To ensure the large capacity and high torque density, further studies are needed for power distribution, compensation components, and averaging the load for all drive train branches.

Study on control of weight and gap for large-scale bearings
The significantly large size and the load bearing capability for bearings have become the bottleneck of the drive train schemes. The optimized design for large-scale bearing, precision test, installation, and gap adjustment are required to secure the operation and lifetime of large-capacity gearbox in addition to appropriately selecting the models of the bearings.

Study on new low-speed-level planetary wheel support
Twin arrays of conoid roller bearings can endure non-torque type load and balance the load for each planetary wheel. The sliding bearing support and flexible pin roll support can also balance the load for each planetary wheel within the rated power and rated speed.

Study on direct maintenance and repair in nacelle
One of challenge to consider is the maintenance and repair for the key components of an offshore wind turbine.

The direct maintenance and repair in nacelle represents that the gearbox can be fixed in the nacelle without being relocated once a fault is encountered, which could lower the cost for operation and maintenance.

Study on advanced manufacturing technology for gear with numerous modules
The study would involve the tool design for gear manufacturing, carburization technology for gear and deformation control technology after thermal treatment and tooth form correction technology for precision gear.

Study on testing large-capacity gearbox
This includes internal shaft system stress analysis; stress test technologies, which contain both facility stress test and field test in the wind farm; facility loading test and fatigue lifetime test acceleration technologies for large-capacity gearbox.

Study on the generator
Apart from the medium-speed gearbox, PMSG has become another mainstream option for both medium-speed and direct-drive schemes. Low-loss-high-reliability scenario at medium voltage level is needed for large-scale generators; to lower the manufacturing cost, collectible winding technology should be utilized; the stator needs to be demountable and sectionizable for direct maintenance and repair in nacelle. Medium-voltage-level converter is inevitable when voltage level is stepped up; subsequently, this would bring up new topics and challenges on new material for power measurement module, generator, and system topology.

6.6.4 Concluding Remarks

Drive train schemes determine the reliability and cost of a wind turbine. All leading countries have initiated research and development on the drive train for large-scale offshore wind turbines to match the requirements for 10 MW and larger models.

Medium-speed-drive and direct-drive schemes gradually became preferred options for the drive train of the offshore wind turbine as the unit capacity keeps increasing. Medium-speed-drive scheme is favorable for 10 MW and greater models, conventional direct-drive scheme would cause economic problem, where superconducting and sub-direct-drive generators are needed. Medium-speed-drive application is a good opportunity for China, which has overall best performance, especially for low-wind-speed region and offshore projects. As the key components for medium-speed-drive technology, the large-capacity gearbox requires optimized design and manufacture for both higher reliability and lower cost.

(X. W. Cui)

6.7 Metocean, Load, and Response of Offshore Wind Turbine Equipment

The use of wind power as a renewable energy resource has been increasingly developed for decades. However, constraints regarding site selection for land-based expansion mean that the transition of wind power development from land to sea is an inevitable trend. Offshore wind energy resources are generally superior to those on land. For example, sea surface roughness is smaller and the wind speed can be up to 25% higher in the 10-km offshore area than on land. Moreover, the intensity of sea wind turbulence is also smaller and the wind direction tends to be reasonably stable, which are conditions beneficial for the mitigation of wind turbine fatigue. In comparison with land-based wind turbine installations, offshore wind energy development does not require consideration of problems associated with land use and noise. In particular, since offshore wind farms are generally closer to the power load center, it is easier for their generated power to be accessed to the power grid. Therefore, compared with land-based wind farms, offshore developments offer obvious advantages in terms of wind resources, site selection, wind turbine assembly capacity, and grid connection.

Despite the evident advantages associated with offshore wind farm developments, the metocean conditions (e.g., winds, waves, and currents) can be very severe and they could be subjected to considerable variation that might tremendously boost the cost of turbines in the life cycle. In designing an offshore wind power system, we can neither directly follow the methodology used for a land-based wind power system nor adapt the design theory applied to offshore oil and gas platforms because of the differences in the characteristics of their structure, environmental conditions, loads, and the fluid–solid coupling involved. Therefore, to develop offshore wind power effectively, it is crucial to consider factors such as the structural characteristics of the offshore wind power system itself, complicated wind–wave environmental conditions, and water–structure coupling, in addition to the air–solid coupling problems associated with a land-based wind power system. In other words, it is vital to assess the wind resources of a development site, elucidate the complicated environmental conditions, and analyze the expected load on the supporting structures. For example, the latter might require consideration of the form of supporting structures and their geometric/motion characteristics, bearing capacity of the foundation, coupling of the superstructure, and characteristics of structural corrosion. In this section, we primarily address the progress of offshore wind power research in the above-mentioned respects and highlight some fundamental scientific and technological issues that require urgent attention.

6.7.1 Metocean Around Offshore Wind Power Farms

Compared with land-based wind farms, offshore developments would confront much more complicated environments. At first, offshore wind turbines and towers could be subjected to the severest effects of typhoons/hurricanes. Secondly, the turbine support structures are affected by waves and currents, the intensities of which are driven by wind over sea surface, which is primarily dependent on atmospheric circulation in troposphere. Thirdly, the seabed around the foundations of the structures could experience scour, liquefaction, and softening. Fourthly, the corrosive effects of the offshore wind farms environment cannot be ignored. In addition, because the coastline of mainland China extends for about 18,000 km, encompassing considerable geographical latitude and complicated climatic conditions, special environmental conditions must be taken into account in some particular sea areas. For example, the Bohai Sea is often affected by the passage of cold waves and subjected a long ice period in winter and spring. In contrast, the East China and South China seas often experience typhoons in summer and autumn. Internal waves that frequently occur in the South China Sea could also pose a potential threat to offshore wind power systems. Therefore, in addition to the average conditions of a specific environment, it is necessary to pay attention to those extreme environmental conditions associated with typhoons, cold waves, internal waves, and ice cover that could affect the local conditions of the wind, waves, currents, and seabed.

1. **Characteristics of offshore wind farms environment**

The environmental characteristics of interest in relation to offshore wind farm development include wind, waves, currents, water elevation, seabed soil, temperature, and salinity as well as marine life. The speed and direction of wind, height and period of waves, speed and direction of currents, and sea surface elevation constitute the fundamental parameters necessary to determine the loads experienced by marine structures. In addition, the attachment of marine organisms represents another important factor that could alter the properties of a structure and further influence its movement characteristics.

In the assessment of metocean conditions, it is necessary to estimate the mean wind speed profile, standard deviation, and turbulent intensity. For a wind speed profile, which can be described by either a logarithmic or an exponential law, the probability generally obeys a Weibull distribution.

To characterize ocean waves, it is necessary to determine the long-term wave spectrum, significant wave height, and spectral peak period. Different wave theories can be applied to describe quantitatively the kinematic characteristics for specific hydrodynamic conditions. The linear wave theory describes waves of small amplitude, whereas Stokes' wave theory can be used for weakly nonlinear waves of larger amplitude. The Boussinesq high-order wave theory and the solitary wave theory can be applied to describe shallow water waves. Three wave parameters, i.e., the wave height H, wave period T, and water depth d, determine the most appropriate wave theory for application to a specific problem. These parameters are used to define

Table 6.8 Range of application of regular wave theories (Reproduced from DNV 2013)

Theory	Application	
	Depth	Approximate range
Linear wave	Deep and shallow	S < 0.006; S < 0.03
Second-order Stokes wave	Deep water	Ur < 0.65; S < 0.04
Fifth-order Stokes wave	Deep water	Ur < 0.65; S < 0.14
Cnoidal theory	Shallow water	Ur > 0.65; < 0.125

three non-dimensional parameters (as shown below) that decide the range of validity of the different wave theories, as shown in Table 6.5 (DNV 2013).

Wave steepness parameter: $S = 2\pi \frac{H}{gT^2} = \frac{H}{\lambda_0}$,

Shallow water parameter: $\mu = 2\pi \frac{d}{gT^2} = \frac{d}{\lambda_0}$,

Ursell parameter: $U_r = \frac{H}{k_0^2 d^3} = \frac{1}{4\pi^2} \frac{S}{\mu^3}$, where 0 and k_0 are the linear deep-water wavelength and wave number, respectively, corresponding to wave period T. Stream function wave theory has a broader range of validity than any of the wave theories mentioned above. It is applicable to most cases before wave breaking occurs, but it does require numerical calculation. The range of application of each order of the stream function wave theory is shown in Table 6.8 (Fig. 6.34).

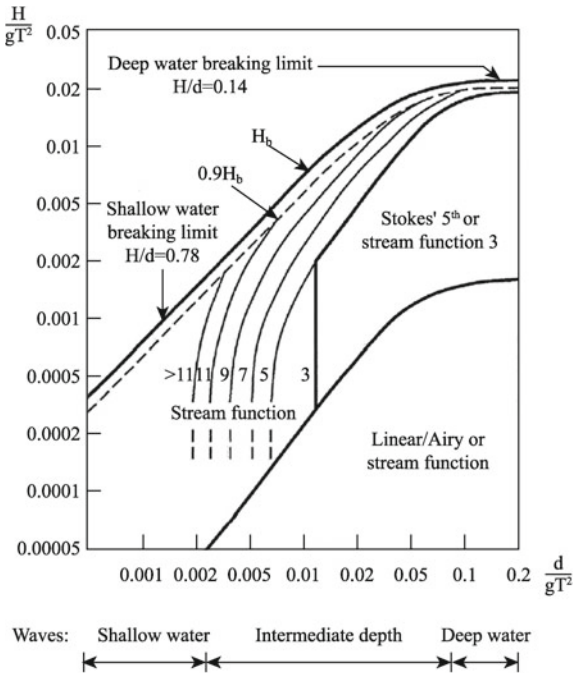

Fig. 6.34 Required order N of stream function wave theory such that errors in maximum velocity and acceleration are <1% (Reproduced from DNV 2013)

Surface waves might break when traveling into a shallow water area where a wind farm might be located. Therefore, this phenomenon must be considered when determining the wave parameters adopted for wind farm design. The properties of breaking waves are influenced by wind–wave, wave–wave, wave–current, and wave–bed interactions; however, the above theories generally cannot describe their kinematics. The relationship between the characteristic parameters of different types of breaking wave and the parameters prior to their breaking should be studied in depth. Depending on wave steepness and seabed slope, breaking waves can be classified into three types: spilling, plunging, and surging waves, as detailed in Fig. 6.35 and Table 6.9.

Spilling breakers, characterized by foam spilling down from the crest over the forward face of the wave, generally occur on gently sloping beaches. Their profiles and kinematics can be described adequately using a high-order stream function solution. Plunging breakers occur on moderately steep beach slopes, and they are noticeably distinct with a well-defined jet of water forming from the crest that falls onto the water surface ahead of the wave. The impinging of this jet onto a fixed structure can lead to high impulsive loads and high local pressures. The modeling of plunging breaking waves is difficult to perform numerically; however, below the still water level, the wave profile and kinematics can be described by a high-order stream function solution. Surging breakers occur on steep beaches where there is considerable wave reflection with some foam forming near the beach surface. The characteristics of this type of breakers are markedly different from those of spilling and plunging breakers and they are unlikely to be of importance for offshore turbine design.

It should be noted that the actions of wind, waves, currents, and other environmental factors have certain interdependence. Shear of wind on the sea surface produces

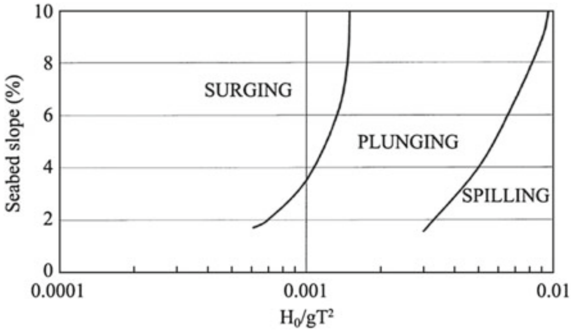

Fig. 6.35 Transitions between different types of breaking wave as a function of seabed slope, wave height in deep water, and wave period. Here, $H0$ is the wave height before breaking (Reproduced from DNV 2013)

Table 6.9 Breaking wave type (Reproduced from IEC61400-3 2005)

Spilling	Plunging	Surging
$\xi_0 < 0.45$	**$0.45 < \xi_0 < 3.3$**	**$3.3 < \xi_0$**
$\xi_b < 0.40$	**$0.40 < \xi_b < 2.0$**	**$2.0 < \xi_b$**

$\xi_0 = \frac{\tan\alpha}{\sqrt{H_0/\lambda_0}}$, $\xi_b = \frac{\tan\alpha}{\sqrt{H_b/\lambda_0}}$, where α is the seabed slope in radians, H_0 is the wave height in deep water, H_b is the wave height at breaking, and λ_0 is the length of the undisturbed wave waves; the shear of strong wind can result in the rise/fall of the sea surface, and interaction between waves and the seabed produces currents. These features account for the strong relationships between environmental factors. Thus, the coupling effects of these environmental factors should be studied thoroughly. The determination of the environmental conditions relevant to offshore design must be based on statistical analysis of observational data sets that should cover periods longer than 10 years, as stressed by DNV (2013). Therefore, it will be necessary to increase the scope of research and expand the acquisition of field observations to establish an appropriate metocean database. This database should include the speed and direction of wind, significant wave height, period and propagation direction of waves, statistical correlation between wind and waves, speed and direction of currents, water level, properties of sea ice, air and water temperature, air and water density, salinity, water depth, marine growth, and other related metocean parameters.

The prediction of wind conditions on average is also important in relation to the construction of both offshore and onshore wind farms. With the integration of wind energy into electricity transmission grids, it is becoming increasingly important to obtain accurate short-term wind speed/power forecasts to ensure efficient scheduling of dispatchable wind power generation. However, the intermittent random nature of wind is incompatible with the requirement for continuous stable wind power production. This represents the main constraint on efficient integration of wind energy into electricity grids. One of the most effective ways to overcome this problem is to establish models for short-term forecasting of wind speed. Numerical weather predictions, statistical analyses, artificial intelligence algorithms, and spatial correlation algorithms constitute four approaches typically used in forecasting.

Time series analysis, which lies within the scope of statistical analysis, has been studied widely and applied in many cases because of its advantages in relation to saving computing resources. This method was proposed and developed by George Box and Gwilym Jenkins. Subsequently, several improved models were developed successively, including the autoregressive conditional heteroscedasticity model, generalized autoregressive conditional heteroscedasticity model, autoregressive moving average model, and seasonal autoregressive integrated moving average model. Liu et al. established a model combining time series analysis and autoregressive conditional heteroscedasticity, whereas Wang et al. developed a model combining time series analysis and fuzzy logic. Both methods have particular advantages and disadvantages, and it is very important to study their applicability to wind speed series in different regions and at different times. Apparently, a short-term wind speed forecast using only wind speed as the input data often ignores the intrinsic physics of the wind and fails to link the prediction model with the physical characteristics of the actual wind speed. This is worthy of particular consideration. Lyu et al. (2016) discussed the characteristics of a short-term wind speed sequence at the Donghai Bridge wind farm in China using different combined models. They compared the accuracy of five models, designed for short-term forecasting of wind speed under single-step and multistep forecasts, with wind speed data measured at the wind farm, based on which they offered their recommendation of one model for the short-term forecasting of wind speed.

In assessing the potential of the wind resource, it is also important to obtain accurate medium- and long-term forecasts of wind speed. Traditionally, approaches used for wind resource assessment have often assumed a stationary wind process with constant mean wind speed. Therefore, the consideration of interannual fluctuation of mean wind speed over many years is essential for establishing models that are more accurate in forecasting medium- and long-term wind speed.

2. Characteristics of extreme environments

Extreme environments refer to typhoons, cold waves, and extreme surface waves that represent the most extraordinary environmental conditions that might affect the survival of offshore wind turbines.

The extreme wind speed of a typhoon and its recurrence period are two important parameters considered in marine engineering design. It has long been assumed that extreme environmental events such as typhoons represent a stationary random process for which the statistical parameters are invariant. Thus, the design parameters of extreme environments have often been determined based on historical observation data. However, in response to global climate change, extreme marine environmental events are occurring with greater frequency, causing increasingly destructive natural disasters. Typical recent examples of this are hurricanes Rita and Katrina that affected the Gulf of Mexico in 2005 and caused one of the most destructive natural disasters in American history. In addition to climatic environmental disasters, other natural phenomena that could affect the marine environment include earthquakes and tsunamis, such as those events responsible for the destruction of Japan's Fukushima nuclear power plant in 2011.

Disasters like those mentioned above have forced engineers and scientists to consider the laws that govern the occurrence of extreme environmental events. For example, based on analysis of observational data, Emanuel found enhancement of tropical cyclone activities in terms of a power dissipation index. Through introduction of extreme value theory to analysis of long-term data of tropical cyclone wind speed and simultaneous water levels of the Mississippi River, USA, Liu et al. found that the return period of Hurricane Katrina should be 50 years instead of 200 years, as estimated previously. Wang and Li argued that tropical cyclones in the northwestern Pacific Ocean present characteristics of a non-stationary random process. Their results indicated that with an increase of air temperature, the annual mean wind speed increases, cyclone intensity increases, and frequency of typhoons and strong typhoons increases. In China, typhoons originating in the northwestern Pacific Ocean frequently affect the East China and South China seas in summer and autumn, whereas cold waves often cross the Bohai Sea during winter and spring. It is evident that the evolutionary trend of both typhoons and cold waves within the context of global climate change should be investigated. Clearly, conventional analysis methods and existing models for forecasting extreme wind speeds based on the stationary-process assumption must be improved. It will be worth exploring a new analysis approach and establishing new forecast models of extreme wind speed based on a non-stationary process of typhoon wind speed.

It will also be necessary to deepen the understanding of the formation, development, dissipation, and propagation of surface water waves induced by extreme environmental events, such as typhoons and cold waves, to establish coupled models of wind–wave interaction in shallow waters. Such models could serve as prerequisites for analyzing extreme hydrodynamic loads of offshore wind power systems. Since the 1960s, the wave propagation equation has been used to describe wave evolution. The prediction accuracy of this model depends considerably on the description of the source function of the equation, including the input of wind energy and the nonlinear effects of waves, wave breaking, and energy dissipation caused by bottom friction. To date, the wave spectrum prediction model has undergone three generations of development, which has resulted in substantial improvement of the methods for describing wind energy input and energy dissipation. Examples of such models in common use include WAM, SWAN, and WaveWatch. Although the third generation of the latter (WaveWatch III), which is a numerical wave model of the full spectrum space, is widely used, the influences of wave age and surface foam on energy input and the effect of wave propagation direction on energy dissipation still require further investigation.

3. **Characteristics of special environments**

For offshore wind farms in certain water areas, special environmental conditions such as sea ice and internal waves should be considered. The corrosive nature of the marine environment is also an important factor that can affect the long-term stable operation of a wind power system.

For offshore wind farms at high latitudes (e.g., the Bohai Sea), it is unnecessary to consider waves during the ice period; however, the action of sea ice on the support structures of offshore wind turbines cannot be ignored. Ice loading depends on the nature and quality of the ice, e.g., the age, salinity, temperature, density, thickness, compression/bending strength, Poisson's ratio, shape and geometry, and speed and direction of movement of the ice, as well as the mode of contact between the ice and the support structures. Ice thickness, t_{ice}, is an important parameter that can be estimated using the following equation:

$$t_{\text{ice}} = 0.032\sqrt{0.9K_{\text{max}} - 50}, \tag{6.3}$$

where t_{ice} is the ice thickness (unit: m), and K_{max} is the frost index (unit: degree days), which is the absolute value of the total 24-h mean temperatures that are <0 °C during the frost period.

In designing an offshore wind farm in water areas where internal waves often occur (e.g., the South China Sea), the influence of internal waves on the structures supporting the wind turbines should be of particular consideration. Internal solitary waves, which can generate strong currents, sometimes disintegrate into a train of smaller solitons when propagating over a continental slope or a seamount. These strong currents and solitons can have important influence on both the stability and the fatigue of the supporting structures. Thus, the laws governing the generation and evolution of internal waves should be investigated.

All structural components of an offshore wind power system are exposed to a very corrosive marine environment. The structure of an offshore wind power system typically comprises four elements: the structure buried in the seabed sediments or covered by disposed solids, the submerged structure, that part of the structure within the splash zone, and that exposed to the atmosphere. The splash zone is the part of the structure that is exposed intermittently to seawater because of the action of tides, waves, or both. It is inevitable that all elements of such structures will be corroded in a marine environment. Corrosion damage can influence the integrity of a structure, reducing its capability to resist loading in various ways. It can act via stress concentration to initiate fatigue cracks, or for extreme loads, it could potentially cause a reduction of the structural component's load resistance function. Corrosion is characterized by dissolution of a metallic surface into ionic form through an electrochemical process. Therefore, full understanding of the electrochemical process is essential for effective implementation of corrosion prevention measures. The process is influenced by fundamental seawater variables such as the types and quantities of dissolved salts and pollutants, dissolved oxygen, temperature, and movement. Marine growth on the submerged structure and in the splash zone should be also considered. Ultimately, different parts of marine structures require unique corrosion protection considerations. Interdisciplinary research involving mechanics, chemistry, and biology should be strengthened to explore the corrosion processes to formulate specific corrosion protection measures for different parts of marine structures.

6.7.2 Support Structure of Offshore Wind Turbines

The support structure for an offshore wind turbine can be divided into two categories: fixed and floating. A fixed-support structure is generally used in shallower areas with water depth of less than 50 m. When the water depth exceeds 50 m, the cost of construction of fixed structures is too high and therefore a floating support structure is used instead.

1. **Fixed-support structure**

The fixed structure used most commonly for offshore wind turbines is a large-diameter monopile, which is often found in European offshore wind farms. Other types of fixed structure include a gravity base, jacket, tripod, tripile, and suction pile. The recently proposed high-rise pile cap structure is used mainly in China. The advantages and disadvantages of various fixed-support structures are listed in Table 6.10.

Compared with conventional oil and gas platforms, the support structures adopted for offshore wind turbines generally have larger diameter piles. The pile diameter of an oil/gas platform is usually only 1–2 m, whereas the diameter of a monopile for an offshore wind turbine is 4–7 m. The diameter of a gravity base is even larger. The cap of the high-rise pile cap structures used in the Donghai Bridge wind farm is

Table 6.10 Comparison of advantages and disadvantages of typical fixed-support structures

Type	Advantage	Disadvantage
Monopile	Simple structure Easy installation High efficiency for Lighter wind turbine and in shallow water Suitable for sea areas with good seabed conditions	Relatively small stiffness Grouting connection problem
Gravity base	Simple structure Easy installation High efficiency in shallow water Good application experience and good reliability	Seabed treatment Measures for anti-scouring Suitable for shallow water and hard sea bed
Jacket	Great rigidity Can adapt to greater depth of water Good application experience and good reliability	High manufacturing cost Large installation equipment Complicated structural force Stress concentration and corrosion of the junction point
Tripod	Relatively large rigidity Can adapt to greater depth of water	High manufacturing cost Complicated structural force Difficult installation
Tripile	Relatively simple installation Can adapt to greater depth of water	High manufacturing cost Complicated structural force Relatively small stiffness
Pile cap	Good adaptability to soft soil foundation High stiffness, integrity, and good collision avoidance performance	Complicated hydrodynamics
Suction pile	Easy installation Low water depth limited Facilitates dismantling and reuse	Not suitable for gravel bed

14 m in diameter. Moreover, as the water depth and the installed capacity of a single turbine increase, the size of the support structures will inevitably increase further.

2. **Floating support structure**

Compared with fixed offshore wind turbines, floating offshore wind turbines have many advantages. They are generally located in deep water and can therefore harvest more abundant wind resources of high quality. Thus, they can have longer operation time for power production at full installed capacity. Floating wind turbines have better survivability or lower risk of destruction in the case of extreme environmental conditions over the design standard, because floating support structures are compliant and can reduce structural loading through allowed movement. In addition, floating wind turbines have better economy, although their cost advantages have not yet been demonstrated fully in the initial stage of their development.

Floating offshore wind turbines were first proposed in 1972 by Professor Heronemus of the Massachusetts Institute of Technology, USA. Since then, a number of research institutes, universities, and enterprises in the USA, Europe, and Japan have undertaken research on floating offshore wind turbines. The tension leg platform or tension leg buoy, spar-buoy, semisubmersible, and pontoon or barge are all types of support structure that have been proposed one after another. The forms of submersible, pontoon, or barge structures suitable as supports for floating wind turbines are still in the stage of research and demonstration. Spars, semisubmersibles, and tension leg platforms are three typical floating support structures already deployed, and their advantages and disadvantages are listed in Table 6.11.

3. **New concept of support structure**

The concept of support structures used for offshore wind turbines is derived from the design of offshore oil and gas platforms. Although offshore oil and gas platforms, either fixed or floating, represent reasonably mature technology, their design is not directly transferable because the support structures for offshore wind turbines have their own special characteristics when compared with oil and gas platforms. First, wind loads on the above-water structures of an offshore wind power system (i.e., the turbine and tower) are much larger than experienced by oil and gas platforms. Considering the characteristics of the large length–diameter ratio of a wind turbine tower, wind loads will force the tower to vibrate violently with large deformation. Consequently, the influence of wind loading on an offshore turbine system is more obvious than on an oil and gas platform. Second, the arm of the wind force is larger than on an oil and gas platform because a turbine tower system is very high. Thus, wind loading will exert a large overturning torque on the support structure of a wind turbine, which will have a detrimental effect on the overall stability of the

Table 6.11 Comparison of advantages and disadvantages of typical floating support structures

Type	Advantage	Disadvantage	Usage
Spar	Simple structure Light weight and good stability Easy design and manufacturing	Restricted to water depth (deeper than 100 m) Special equipment for installation On-site maintenance	Several MW prototype turbines in use, e.g., Hywind and Goto-FOWT
Semisubmersible	Less restriction of water depth Installation in dock Can be towed in dock for maintenance	Big weight Complicated structure with many connecting parts Difficult design and manufacturing Should be equipped with an expensive active ballast system	Several MW prototype turbines in use, e.g., WindFloat and Fukushima-Forward
Tension leg platform	Less restriction of water depth Light weight and good stability Installation in dock	Strong loads on mooring system Special equipment for complicated on-site installation	prototype turbines being planned but without use, e.g., Blue H TLP and GICON-TLP

system, including the seabed foundation. Third, for floating wind turbines, wind loads will cause much larger translation and rotation of both the floating platform and its mooring lines. Thus, the nonlinearity of the movement of the system is much stronger. Therefore, because of the high overturning moment and the strong nonlinear motion of the structures, it is urgent that new concepts be sought for the design of support structures for offshore wind turbines.

In recent years, some special schemes for floating offshore wind turbines have been designed, such as the installation of multiple wind turbines on a floating platform, the WindSea scheme of FORCE Technology, and the concept of sailing-type wind farms proposed by Japanese researchers. The State Key Laboratory for Marine Engineering of Shanghai Jiao Tong University proposed a new multicolumn tension leg floating wind turbine called the WindStar TLP. Zhao et al. performed model tests of the WindStar TLP system in a wave tank with various wind speeds and currents. Their results demonstrated that the eigenperiods of the WindStar TLP at its six freedoms of degree were far beyond the normal wave period, suggesting good motion performance.

Each type of offshore wind turbine system has specific advantages and disadvantages. It is highly important to optimize a safe economic system in accordance with the wind resources and environmental conditions, e.g., wind, waves, currents, seabed, and geology. In particular, comprehensive research on innovative concepts for megawatt floating wind turbines is urgently required.

6.7.3 Hydrodynamic Loads on Structural Support of Marine Wind Turbines

An offshore wind power system involves not only the aerodynamic loading and aerodynamic response of the turbine and tower but also the hydrodynamic loading and hydrodynamic response of the supporting structure. This section focuses on the hydrodynamic loading experienced by the support structures, including current loads, wave loads, and ice loads. The estimation of current loads is reasonably simple, but the derivation of wave and ice loads is worthy of particular attention.

1. **Current loads**

Apart from wind-generated flow, tidal flow, and density flow, currents can be manifested as flows that accompany storm surges and internal waves, as well as flows generated via the interaction of waves with terrain and through atmospheric pressure changes. Current loads can be calculated using the following equation:

$$F = \frac{1}{2} C_{\mathrm{d}} \rho U^2 A, \tag{6.4}$$

where U is the current velocity, A is the area of projection of a structure member perpendicular is the density of to the flow direction, C_d is the drag coefficient, and water.

2. **Wave loads**

With the continuing development of offshore wind power, the installed capacity of wind turbine systems is becoming larger, which means bigger supporting structures are required, irrespective of whether a fixed or a floating platform. However, offshore wind turbines are mainly constructed in shallow water where the wavelength is very likely to be shorter in comparison with deep water. Therefore, the non-dimensional scale of the structure D/L (where D is the dimensional scale of the structure and L is the wavelength) is very likely to be close to the defining value of large- and small-scale structures, which is $D/L = 0.2$ or 0.15. Typical examples are the high-rise pile cap structures used in the Donghai Bridge wind farm in the East China Sea and the composite cylindrical foundations of the wind turbines of the Qidong wind farm in Jiangsu Province, China. Consequently, it is not easy to decide whether such structures are small or large scale, which causes uncertainty when estimating the wave loading on structures of this scale. Thus, engineers have to adopt safe factors in their design but without reliable guidance on how to determine them. Therefore, it is of great importance to study the method adopted for the estimation of wave loading of this scale of structure, which in the following we refer to as a medium-scale structure.

Wave loading on a structure is influenced by the effects of water viscosity, wave diffraction, and nonlinearity. To understand the mechanism of wave loads, a number of parameters have been proposed to describe the problem, among which the non-dimensional scale of the structure is crucial. For a small-scale structure, Morison proposed a semiempirical model, which equates wave loads to the summation of two parts, as follows:

$$F = \frac{1}{2} C_d \rho D |U| U + C_m \rho A \frac{dU}{dt}, \tag{6.5}$$

where F is the wave force acting on unit length of the structure, C_d is the drag coefficient, is the water density, D is the structure C_m is the inertia force coefficient, diameter, A is the cross-sectional area of the cylinder, and U is the flow velocity component perpendicular to the cylinder. The first part represents the velocity force produced by the undisturbed velocity field, and the second part represents the inertia force produced by the fluid acceleration. For a large-scale structure, the wave force can be described by diffraction theory, which assumes inviscid potential flow of water with a linearized free surface condition. Issacson argued that a cylinder is large if $D/L > 0.2$ and that wave loading on a vertical cylinder should be estimated using diffraction theory to consider diffraction effects. Otherwise, the cylinder is small and its wave loading should be estimated using the Morison model to consider viscosity effects. However, Issacson does not explain why $D/L = 0.2$ is used to distinguish small and large structures. Some studies have proposed using $D/L = 0.15$ as the demarcation, which shows that the criterion for defining small and large structures is unclear. It could be speculated that a medium-scale range might exist between small and large scales, although this would raise certain questions, e.g., whether the wave force of a medium-scale structure is dominated by the effects of viscosity or inertia, both, or neither. There are few offshore structures for which $D/L \approx 0.2$. Thus, few studies have been undertaken to resolve this problem. However, this problem is inevitable in the design of support structures of offshore wind turbines, especially megawatt turbines. Therefore, it is essential to delineate the medium-scale range and to determine the components of the wave force acting on medium-scale structures.

Chen et al. (2016) established a three-dimensional numerical wave flume based on OpenFOAM, and they studied the characteristics of the linear wave force acting on vertical surface-piercing cylinders. By solving the Navier–Stokes equations and the Euler equation with consideration of the free surface, they were successful in deriving the viscous force acting on the cylinders. Then, they discussed the influence of cylinder size on both the viscous force and the diffraction force for the case of linear waves in finite water depth. Based on their analysis, they proposed a new concept of medium-scale structure and a new hydrodynamic classification of marine structures with wave forces estimated using different methods, as outlined below.

A marine structure is defined as small scale if $D/L < 0.02$. For small-scale structures, the viscosity effect on wave force cannot be ignored, whereas the diffraction effect is not obvious. The wave force should be calculated using the Morison formula. When the structure is of very small scale (i.e., $D/L \ll 0.02$), the wave force will also exhibit a diffraction effect attributable to the influence of the free surface, in which case Cm can be assigned the value of 1.8.

A marine structure is of large scale if $D/L > 0.2$. For large-scale structures, the viscosity effect on wave force is negligible, whereas the diffraction effect is obvious. The wave force should be calculated using diffraction theory or the Morison formula with the value of C_{m} modified based on linear diffraction theory.

A marine structure is of medium scale if $0.02 < D/L < 0.2$. For medium-scale structures, both the viscosity effect and the diffraction effect on wave force are not obvious, and the error in the wave force when neglecting the two effects is less than 2 and 4%, respectively. In this case, the Froude–Krylov formula represents the most convenient approach to the calculation of the wave force. However, if the Morison formula was used, the values of C_{d} and C_{m} should be 0.6 and 2, respectively.

It should be noted that these conclusions are limited to linear waves. The dependence of wave force on the Keulegan–Carpenter (KC) number and the Reynolds number under strong nonlinear waves requires further investigation.

Whether using the Morison equation or the diffraction theory to calculate the wave loading on marine structures, the kinematic theory of wave motion is determined a priori, based on which the wave force is obtained through the velocity field and the pressure field of wave motion. However, most offshore wind farms are located in shallow water. When deep-water waves propagate to a wind farm, they will inevitably interact with the terrain, causing wave deformation or even wave breaking. The interaction of these strong nonlinear waves with marine structures is much more complicated than that of regular waves. Unfortunately, there is no mature theory for the description of the kinematics of such strong nonlinear waves. Therefore, the interaction between nonlinear waves and marine structures is worthy of particular concern when estimating the wave loading on offshore marine structures in shallow water.

The wave slam force is important with regard to offshore platforms supporting wind turbines. As stated in IEC61400-3 (2005), wave slam occurs when a horizontal or inclined structure is engulfed by a rising water surface as a wave passes. The highest slamming force occurs for members at the mean water level, and its direction of application is approximately vertical. Wave slap is associated with breaking waves, and it can affect members at any inclination in the plane perpendicular to the wave direction. The highest slapping forces occur above the mean water level. The actual hydrodynamics of slamming are highly complicated and the precise shape of the water surface at the instant a slam occurs has considerable effect on the slam force. The equation for wave slam force is commonly written as follows:

$$F = \frac{1}{2} C_{\mathrm{s}} \rho D |U_{\mathrm{s}}| U_{\mathrm{p}}, \tag{6.6}$$

where is the where water density, D is the diameter of the structure, C_{s} is the slamming force, U_{s} is the rate 1/2 and 2 coefficient with a value for a cylinder of between at which the water surface crosses the cylinder diameter, and U_{p} is the velocity of water particles normal to the cylinder.

Wave loads from breaking waves should be considered in the design of a structure supporting an offshore wind turbine if the wind farm is located in a region where waves are likely to break. As stated in DNV (2013), wave loading from breaking waves depends on the type of breaking waves. For plunging waves, the impact load can be expressed as follows:

$$F = \frac{1}{2} C_{\mathrm{s}} \rho A U^2, \tag{6.7}$$

where U denotes the water particle velocity in the plunging wave crest, ρ is the mass density of water, A is the area on the structure assumed exposed to the slamming force, and C_{s} is the slamming coefficient, which is larger than 3.0 and less than 2π for a smooth circular cylinder.

For surging and spilling waves, one approach to the calculation of the associated wave forces on a vertical cylindrical structure of diameter D, divides the cylinder into a number of sections. As the breaking wave approaches the structure, the instantaneous wave elevation close to the cylinder defines the instant a section is hit by the wave and when it starts to penetrate the sloping water surface. The instantaneous force per unit vertical length on this section and on the underlying sections, yet to fully penetrate the sloping water surface, can be calculated as follows:

$$f = \frac{1}{2} C_{\mathrm{s}} \rho D U^2, \tag{6.8}$$

where U denotes the horizontal water particle velocity, ρ is the mass density of water, and C_s is the slamming coefficient:

$$C_s = 5.15\left(\frac{D}{D + 19s} + \frac{0.107s}{D}\right), \quad 0 < s < D, \tag{6.9}$$

where s is the penetration distance for the structure, which is the horizontal distance from the periphery on the wetted side of the cylinder to the sloping water surface, measured in the direction of wave propagation. For fully submerged sections, the Morison equation is used.

Recently, Chen et al. (2017, 2018) studied the wave load characteristics of the high-rise pile cap structure used in the Donghai Bridge wind farm. When a wave slams the bottom of the cap, the pressure in the water body below the cap can be increased substantially. Thus, the wave loading on the downstream piles can be increased significantly and that on the upstream piles can be decreased in comparison with results obtained without consideration of wave slamming on the cap. Therefore, parameterization of the impact or slam loads from breaking waves on marine structures is a topic that requires further study.

3. **Ice loads**

Ice loading and ice-induced vibration are critical for wind turbine structures constructed in waters that have severe winter climatic conditions. At present, theory in respect of this field is very immature and further in-depth research is necessary.

Ice loading can manifest as either static loading from a fast ice cover or dynamic loading caused by moving ice floes driven by the wind or currents. Static ice loads induced by a fast ice cover include horizontal loads due to both temperature fluctuation (thermal ice pressure) and water level fluctuation. Static loads also result from pressure associated with hummocked ice and ice ridges via subduction and ridging processes, and from masses of ice frozen to the structure. Dynamic ice loads primarily refer to horizontal loads resulting from moving ice floes.

Many factors can affect the ice load, e.g., meteorological factors (temperature, wind speed and direction), hydrological factors (salinity, water temperature, water level, flow velocity and direction), geometric, physical, and mechanical properties of the ice (age, thickness, bending strength, crushing strength, icing speed, fracture law, ice size, drifting speed and direction of ice floes), geometry of the structure (size, cross-sectional shape, surface slope), and ice–structure interaction (contact, friction, and collision between the ice and the structure).

Dynamic ice load has attracted considerable attention because it induces structural vibration, which probably causes dynamic locking. For a vertical cylindrical structure with diameter D, the dynamic ice load can be expressed as follows (IEC 61400-3 2005):

$$H_{\text{dynv}} = H_{\text{d}}\left(\frac{3}{4} + \frac{1}{4}\sin\left(\frac{f_n}{2\pi}t\right)\right), \tag{6.10}$$

where t is time, f_n is the eigenfrequency of the structure, and H_d is the horizontal ice load applied to the structure by drifting ice floes, which can be estimated using the following equation:

$$H_\mathrm{d} = k_1 k_2 k_3 t_\mathrm{ice} D \sigma_c, \tag{6.11}$$

where k_1 is the shape factor that reflects the shape of the support structure on the ice-impact side; k_2 is the contact factor representing the ice contact against the support structure, which accounts for the fact that ice under continuous crushing is not in contact with the entire nominal surface of the support structure, except at the onset of movement when it is completely frozen to the support structure; k_3 is the factor that defines the ratio between the ice thickness and the structure diameter, which takes the three-dimensional stress state of the c is the contact point into consideration; t_ice is the ice thickness; and crushing strength of the ice.

Various formulas are available for the calculation of ice load; however, their results are often very different. The values of the coefficients involved are empirical and without consensus. Although IEC61400-3 (2005) recommends a variety of calculation models for static and dynamic ice loads, the values of the relevant coefficients have not been verified sufficiently by field or experimental data. Therefore, the DNV (2013) emphasizes that theoretical methods adopted for the calculation of ice loads should always be used with caution.

6.7.4 Dynamic Response of Marine Wind Power Turbines System

An offshore wind power system represents a coupled system, i.e., the structural components (above-water wind turbine and tower, floating bodies, submerged cables or moorings, piles, and soil foundation) and their associated aerodynamic and hydrodynamic forces, deformations, and motions are all inseparable. For a floating offshore wind power system, the motion of the floating body and underwater cables or anchor chains under the action of coupled wave–current hydrodynamic forces is much larger than that of the corresponding structures of conventional oil and gas platforms. The motion of the wind turbine and the tower, and the high overturning moment from the aerodynamic forces, further intensify the movement of the supporting structures. For a fixed offshore wind power system, the aerodynamic forces on the above-water structures and the hydrodynamic forces on the underwater structures not only cause their own motions but also apply considerable overturning torque to the soil foundation. Therefore, an offshore wind power system is a strongly coupled system for which the coupling motions represent the primary problems in relation to the economics, stability, and survivability of the engineering. Consequently, analysis of the coupling forces and the dynamic responses represent the frontier of scientific research in this field.

For such strongly coupled systems, it is preferable to consider the blade, hub, tower, support structures, soil foundation, and ideally the servo controller as a single entity when performing comprehensive study. However, it is currently very difficult to establish a global coupling model or method for analysis of the complete aerodynamic and hydrodynamic responses of these systems. Therefore, decoupling represents an indispensable approach in which coupled models are developed for local subsystems. An effective method is to analyze separately the aerodynamic response of the wind turbine, hydrodynamic response of the floating body, coupling of the underwater structures, and interaction between the piles and soil foundation. Here, excluding the aerodynamic response of the turbine and tower, we focus on the fluid–solid coupling of the floating body, fluid–solid coupling of the underwater components (i.e., moorings and piles), coupling between the above-water and underwater structures (i.e., turbine, tower, floating body, and moorings), and fluid–solid–soil coupling.

1. **Fluid–solid coupling of floating bodies**

For floating wind turbines, the floating base structure and its underwater mooring system are inevitably influenced by the motion of both the turbine and the tower attributable to their wind loading. The translation and rotation of the floating base and the movement of the moorings of floating wind turbines are much greater than found for conventional offshore oil and gas platforms, which result in much stronger nonlinear effects. The nonlinear effect of water waves generates the average drift of the floating body as well as low- and high-frequency vibrations that include springing and ringing. The horizontal displacement of a platform caused by slow drift, which is often very large, can cause operational difficulties and cable break. Low- or high-frequency vibration can stimulate low- or high-frequency resonance of the floating body, respectively. At the beginning of the 1970s, high-frequency vibrations such as springing and ringing were first noticed, which prompted considerable research. It was eventually realized that springing is a steady-state response, often associated with second-order wave effects (e.g., the sum frequency effect), whereas ringing is a strong transient response, triggered by the passage of a single high, steep wave event, or a wave train. Both of them could cause structural fatigue and sudden vibration of a platform. However, most relevant studies focused on compliant conventional offshore oil and gas platforms (especially tension leg platforms). With consideration of the structure of offshore wind turbine systems, Marino et al. recently proposed an efficient model for the analysis of the influence of random nonlinear waves. They found the contribution of the nonlinear effect to the structural response significant, whereas the linear theory underestimates wave height, and steep waves lead to structural resonance, similar to the ringing phenomenon. They also highlighted that further study will be necessary to explain this phenomenon fully. Indeed, for an offshore floating wind turbine system, the mutual restraint and coupling between the floating body and the mooring lines are much stronger than for a conventional floating oil and gas platform system. Therefore, the high degree of nonlinearity needs to be studied thoroughly, and investigation of an added mass and damping coefficient should be conducted because of its importance in modeling the motion of a floating body.

Strong nonlinear waves and their interactions with offshore structures in the case of severe ocean climate have become the focus of ocean engineering, which is particularly critical for floating wind turbine systems. It has been realized that simply increasing the design standard of wave height is not a satisfactory method for considering severe conditions, because it is important to consider the transient characteristics of wave breaking caused by strong nonlinearity and its mechanism of action on offshore structures. Currently, there are no effective theories or models capable of addressing such problems as slamming from a breaking wave on an offshore structure and the resultant transient nonlinear dynamic responses.

In constructing an offshore wind farm in a high-latitude area, the interaction between the ice and the structure is particularly important, especially the interaction between crushed ice and the vertical structures. The natural vibrations of a structure will influence the break-up frequency of fast ice cover or of a large ice floe. If the ice break-up frequency is tuned to the natural frequency of the structure, then the lock-in phenomenon is inevitable and ice-induced resonance will occur. It is clearly critical to try to avoid this phenomenon through design. The criterion for the occurrence of tuning is recommended by the DNV as:

$$\frac{U_{\text{ice}}}{t_{\text{ice}} f_{\text{n}}} > 0.3, \tag{6.12}$$

where U_{ice} is the speed of the ice floe, t_{ice} is the ice thickness, and f_{n} is the natural frequency of the structure.

As for the analysis of ice-excited vibration, the loading can be assumed to follow a serrated profile in the time domain, as shown in Fig. 6.36. The maximum value of the load is equal to the static horizontal ice load. The load is applied with a frequency that corresponds to the natural frequency of the structure. For conical structures, the break-up frequency of the ice is assumed independent of the natural vibrations of the structure. It can be estimated using the following equation:

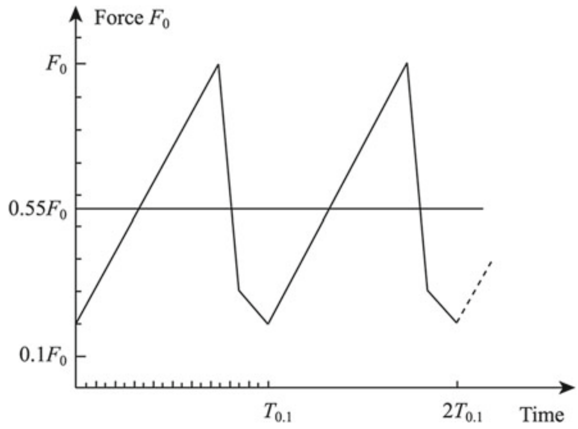

Fig. 6.36 Serrated load profile for dynamic ice load (Reproduced from DNV 2013)

$$f_{\text{ice}} = \frac{U_{\text{ice}}}{L}, \tag{6.13}$$

where L is the crack length within the ice, which can be calculated as follows:

$$L = \left(\frac{\frac{1}{2} E t_{\text{ice}}^3}{12 \gamma_w (1 - \nu^2)} \right)^{0.25}, \tag{6.14}$$

where E is Young's modulus of the ice, ν is Poisson's ratio of the ice, and γ_w is the specific gravity of water. This formula does not involve the effect of ice speed, which could induce large error.

Ice–structure interaction is extremely complicated; there are few relevant theories, and it is very difficult to simulate numerically. Consequently, it is imperative that first-hand observational data be accumulated from offshore engineering structures that are already built, to provide a reliable basis for theoretical analysis and numerical modeling of the coupled interaction.

2. **Fluid–solid coupling of underwater components**

Underwater components refer mainly to the cables or mooring lines of a floating body and the piles of a fixed-support structure. Generally, the scales of these components are smaller than the characteristic wavelength of surface waves, i.e., they have a large length–diameter ratio. Their hydrodynamic responses depend upon the flow velocity, Reynolds number, ratio of mass of the structure over its water displacement, ratio of the structure diameter over the wavelength, and stiffness of the structure.

When waves or currents pass through underwater components, vortex shedding occurs, which results in an asymmetrical flow pattern and pressure field around the component. A resultant periodic force exerted on the component causes vortex-induced vibration (VIV) of the component, which is the main reason for fatigue failure of offshore structures. When the VIV frequency is close to the natural frequency of the component, the lock-in phenomenon occurs, which can lead to the failure. The VIV can be transverse to or in line with the flow direction. There have been many studies on transverse VIV but few on in line VIV, and even fewer on their coupling. Previous research on VIV in relation to the flow field and the structural characteristics has focused primarily on simple steady flows (e.g., uniform unidirectional flow) and rigid cylindrical structures.

Although much research has been undertaken on the hydrodynamic response of underwater components, it remains important to consolidate the understanding in relation to flexible structures with strong nonlinearity when subject to complicated hydrodynamic conditions. For example, under the action of shear flows, a flexible cylinder with a large length–diameter ratio could present multimodal lock-in, where the response to each mode would be related to the lock-in frequency distributed along the cylinder. Therefore, it is also necessary to consider the combined action of waves and currents or even special hydrodynamic environments such as internal waves and freak waves.

3. **Coupling of structures in air and water**

As mentioned above, it is currently extremely difficult to undertake complete or global coupling analysis or simulation for an entire offshore wind turbine system, which includes the above-water structures, underwater structures, and soil foundation. For floating wind turbine systems, it is reasonable to consider the coupling of the floating body with its underwater mooring lines or tension legs, with the influence of the above-water structures into account by simply transferring the wind loading to the floating body. Guo et al. claimed that previous research on this issue has mainly used quasistatic methods to simulate the underwater mooring lines, by considering the static restoring force of the moorings but neglecting their inertia and viscous hydrodynamic resistance. The FAST program, developed by the American Renewable Energy Laboratory, is an example of software commonly used for response analysis of offshore wind turbine systems. It performs analysis of systems using modal and multi-body dynamics methods. It calculates the restoring force of the mooring system via the quasistatic method, but it ignores the inertial and viscous forces of the mooring lines. It also excludes structure elasticity, and it only considers part of the full degrees of freedom of the structure. For example, it only considers the first two modes of the blades by taking the modes and their frequencies as input data, which are calculated in advance by other software. However, with increasing water depth, the length of the mooring lines would increase considerably and the dynamic effect of the mooring lines would become significant. The quasistatic method will overestimate the surge amplitude of the floating body. It has been demonstrated that the hydrodynamic resistance of the mooring lines will cause significant difference in the response of floating wind turbine systems, especially in the displacement of the floating body and fatigue loading. In addition, the multi-body dynamics method with only the finite degrees of freedom considered simplifies the flexible components of the system. Thus, it cannot properly describe the deformation and response of the elastic components of the system and their coupling with each other, which is very important for large-sized blades.

It is essential to consider the dynamics of the mooring lines and to further establish an analytical method and a model of the local subsystem that includes the blades, tower, floating body, and mooring lines, cables, or anchor chains for dynamic analysis of floating systems. Guo et al. established a time domain model for an entire wind power system including catenary anchor chains based on finite element numerical simulation. The inertial force and the hydrodynamic resistance of the anchor chains are all considered. Their results showed that the dynamic effect of the anchor chains leads to large variation of the tension force amplitude of the anchor chains, i.e., the maximum tension will increase and the minimum tension will decrease. With increasing displacement of the floating body, the minimum tension could be reduced to zero, implying that the anchor chain is relaxed. In addition, when the wave frequency is far higher than the system frequency, the dynamic effect of the anchor chains accelerates the transient attenuation of the structure but it does not affect the steady small-amplitude movement of the floating body. When the wave frequency is close to the frequency of the system, the dynamic effect of the anchor chain reduces the displacement of the floating body markedly. The inertial and viscous forces of the anchor chain increase the overall stiffness of the system. The dynamic restoring force is related not only to the displacement but also to the velocity of the surge of the floating body, implying that restoring stiffness is directional.

4. **Coupling of fluid, solid, and soil**

The interaction or coupling of the fluid, structure, and soil is another important issue in offshore wind power engineering, especially for fixed structures for which it is fundamental to the stability and safety of the foundation of the wind turbine system. For fixed structures, it is necessary to consider the coupling between waves, currents, piles, and soil. This requires in-depth investigation of the coupling mechanism between factors such as cycling wave loads, coupling loads of waves and currents, pile vibration, soil pore pressure, scour and liquefaction of the seabed, and ultimate bearing capacity of the soil foundation.

(1) Wave–current–pile–seabed coupling

The pile diameter of the support structure of a fixed offshore wind turbine is generally very large, especially in the case of a monopole, i.e., up to 5–7 m. Moreover, with the development of large-capacity wind turbines, the monopole diameter will become even larger, unlike the case for conventional oil and gas development platforms. Structures with larger diameter will introduce three additional problems. First, the KC number will become smaller (about 0–10), which has important influence on the development of scour around the piles. Second, the length–diameter ratio of the piles will become smaller, and the scour depth around the piles will account for a larger portion of the pile penetration. Third, the piles will have greater bending stiffness, serving as rigid piles during their bearing process, which will make the mechanism of pile–soil interaction markedly different from that of ordinary flexible piles.

Because of the smaller KC number, there is no reliable method for prediction of the scour depth around a large-diameter pile. In coastal areas, the simultaneous actions of waves and currents will make the problem even more complicated. Previous studies have tended to investigate scour around a pile under the action of either waves or currents, while few have considered scour around a pile under the simultaneous actions of both. Qi et al. performed laboratory experiments on scour and soil response around a large-diameter pile under the combined action of waves and currents to elucidate the wave–current–soil–pile coupling mechanism. They focused on the scour mechanism, ultimate scour depth, and pore pressure response of the soil. They found scour under the joint action of waves and currents is governed mainly by horseshoe vortices. Both the scour rate and the ultimate scour depth under the combined action of waves and currents are greater than under the action of current alone, especially in the case of small current velocity (i.e., less than the incipient velocity of sediments). Because of the nonlinear interaction of waves and currents, the superposition of currents with wave propagation generates a larger scour rate and ultimate scour depth than the superposition of currents against wave propagation. Scour depth increases rapidly with increasing current velocity when the KC number is small. When the KC number is large, current velocity has no evident influence on scour depth. In particular, Qi et al. found that ultimate scour depth is strongly dependent on the Froude number defined with mean velocity. Hence, they established a new model for estimation of ultimate scour depth, which predicts experiment results with error of $\pm$ 25%.

Scour occurring around a pile, whether local or general, causes the bearing capacity of its soil foundation to decrease. In particular, weakening of the horizontal bearing capacity caused by scour is obvious for a pile with reasonably shallow penetration depth. To describe the horizontal bearing capacity of a soil foundation, the pile is often considered an elastic beam and the surrounding soil a series of springs along the pile. By establishing an equilibrium relationship between the elastic beam and the surrounding springs, the displacement of the pile under a certain horizontal load can be obtained. There are several different methods used to estimate the horizontal bearing capacity corresponding to different descriptions of the constraints of the soil springs. Currently, the method used most widely is the p-y curve proposed by the API and DNV (2013) for the case of sand. However, the p-y curve is based on limited field experimental data, where the pile diameter was only 0.61 m; it could produce considerable error when applied directly to large-diameter piles. Therefore, the influence of scour on the horizontal bearing capacity of piles has attracted increasing attention from engineers and scientists. Two principal factors have been considered in the literature. First, scour leads to change of the mechanical properties of the surface soil, causing it to enter a state of excess consolidation. Second, the dimensions of the scoured hole make a difference. Recently, Qi et al. proposed a revised p-y curve designed to consider the effect of local scour by introducing the concept of effective soil depth. Qi and Gao established a three-dimensional finite element model to simulate pile–soil interaction, obtaining p-y curves for different parameters. They analyzed the scour effect on pile–soil interaction, and they highlighted that the response of soil around a typical monopole, which bears the horizontal loading, cannot be predicted satisfactorily by the traditional p-y curve when scour occurs. Comparison of the results of local and general scour demonstrated that the effect of scour on the bearing capacity of large-diameter piles depends on the slope of the scour hole.

(2) Pile–soil coupling

The stability of the structure supporting an offshore wind turbine and its soil foundation is the key factor to ensure long-term safe operation. The towering characteristics of offshore wind turbines bring a series of design difficulties. For example, it is not easy to determine in advance the failure manner and location. Failure might occur in the support structure or the soil foundation because of fatigue or loading that exceeds the design limits.

The support structure of a towering wind turbine bears a huge overturning moment, which results in large compressive pressure in the leeward side of the pile and large tensile pressure in the windward side of the pile. This loading state introduces considerable difficulties regarding the design for the bearing capacity of the system and subsidence control of the soil. To ensure safe operation of wind turbines, the stiffness of the entire system, including wind turbine, support structure, and soil foundation, should meet its frequency response requirements and avoid large vibration of the system. Because of the special requirements of wind turbine equipment, the frequency range of the entire system is usually narrow. The supporting structure of an offshore wind turbine, as a vertical cantilever above the mudline, reduces the natural frequency of the structure and magnifies the dynamic effect of loading. Therefore, ensuring the safety of the structural design might prove difficult using conventional quasistatic analysis; thus, the development of an appropriate dynamic analysis method is essential.

There are two primary mechanisms of failure of soil foundations. The first is when the maximum load exceeds the ultimate bearing capacity of the soil foundation. The second is due to long-term cycling stress of hydrodynamic loading, which decreases the strength of the soil foundation. When the water depth is large, the hydrodynamic and wind loads result in large horizontal displacement of the cantilever structure above the mudline, which causes considerable difficulties for engineers when developing a design to govern the horizontal deformation of the cantilever. Therefore, it is an important part of the engineering design process to choose a reasonable model for both static and dynamic analyses of the support structure and soil foundation of wind turbines to produce accurate estimations of the structural stress and deformation. The deformation and ultimate bearing capacity of the soil foundation are important problems in the design and analysis of an offshore wind power system. In coastal areas, cyclic wave loading will cause a cyclic transient response of excess pore water pressure of the soil, sometimes accompanying a cumulative response of the pore water pressure, which could cause seabed liquefaction. The cyclic transient variation of excess pore water pressure and the occurrence of liquefaction have substantial impact on scour around a pile under the concurrent actions of waves and currents. In combination with the high overturning moment, this mechanism could result in the bearing capacity of the soil foundation being diminished or even lost, thereby threatening the structural stability and safe operation of an offshore wind turbine.

In brief, scour and liquefaction caused by the cyclic action of waves and their influences on the stability of an offshore wind power system involve complicated coupling of the fluid, structure, and soil. It is essential to deepen understanding of both the coupling dynamics of scour and liquefaction under the actions of high overturning moment and cyclic hydrodynamic loading, and the mechanism of the coupling dynamic process on the bearing capacity of the soil foundation.

6.7.5 Concluding Remarks

The exploitation of wind power utilization has been continued for decades, and the development of offshore wind power systems has currently become an active area for sufficient and efficient utilization of renewable energy. Offshore wind power systems differ from land-based wind power systems and offshore oil and gas platforms in terms of their structural system, environmental conditions, loading characteristics, and fluid–structure interactions. It is therefore an urgent task to have an in-depth understanding in these characteristics specific to offshore wind power systems by new theories, models, and methods applicable for these structures.

Offshore wind power systems face complicated environmental conditions. It is essential to accurately assess wind resources for efficient grid access to by establishing elaborate prediction models based on wind field data series. At the same time, we need to develop new theoretical approaches to describe extreme environmental conditions such as hurricane/typhoon, rouge wave, breaking waves, particularly in the context of global climate change. These representative scientific problems should be addressed in relation to ongoing offshore wind farm construction.

New theories and models in this regard are required to be capable of calculating both aerodynamic loads on turbine hub, blades and tower, and hydrodynamic loads due to wave, breakers, vortex shedding and floating ice. In the meanwhile, it should be paid more attention to explore new concept floating wind power system for economic, effective, stable and safe utilization of offshore wind power.

An offshore wind power system is a strongly coupled system. On the one hand, coupling theoretical models and optimization methods should be actively developed to deal with the overall interaction between metocean environment and integrated structural system including wind turbine, tower, support structure, and soil foundation. On the other hand, decoupling analysis remains indispensable considering difficulties in developing comprehensive coupling models. So it is more practical to rely on coupling analysis theories and models for the fluid–solid interaction of local subsystems such as coupling of wind and above-water structures, of surface wave and floating body, of wave, current, and submerged structures and fluid–structure–soil coupling.

(J. F. Zhou)

6.8 Intelligent and Green Manufacture of Wind Power Equipments

Wind power equipment manufacturing is an important part of China's manufacturing industry. The State Council has issued strategic policy of "innovation drive, quality priority, green development, structure optimization, and talent orientation," and ratified a few projects such as manufacture industry innovation center construction project, intelligent manufacture project, industry strong base project, green manufacture project, and high-end equipment innovation project. Priority is always given to green and intelligent manufacture.

As far as green manufacture is concerned, green technologies are applied to the design, manufacture, installation, operation, and recycle of equipment in such a way as to facilitate energy conservation, low-carbon, low-pollution, cyclic utilization, and sustainable development. In the meanwhile, intelligent manufacture is to further intelligentize and fully perfect the manufacturing process, relying on intelligent equipment, industrial control network, corresponding software, big data, and other automatic, digital, and networked technologies. There are both ties and differences between green and intelligent manufactures.

6.8.1 Greenization of Wind Power Equipment Manufacture

To accelerate China's ecological civilization construction, MIIT formulated an Industrial Green Development Plan (2016–2020). The targets of the plan are as follows: By the end of 2020, the green development concept becomes the basic requirement of the whole industrial sectors and processes, the promotion mechanism of industrial green development takes shape, the green manufacture industry serves as the new engine for economic growth and the new advantage of international competition, and the overall level of industrial green development witnesses significant progresses.

Wind power equipment is a green energy equipment, and its green manufacturing process consists of a crucial part of the green development of industry. As the wind power industry is rapidly growing, the green manufacturing of wind power equipment has become more essential for the sustainable development of the wind power industry in the twenty-first century. As a modern manufacturing mode accounting for environmental influence and resource efficiency, green manufacturing mainly involves the improvement of manufacturing environment, reduction of manufacturing loss and energy consumption, recycle of wind power equipment, etc.

1. **Current status and developing trend**

The manufacturing process of wind power equipment is a systematic engineering that relates to the manufacturing of raw materials and main parts, equipment related general assembly, transport, installation, operating maintenance and repair, recycle, and remanufacturing, and so on.

The green manufacture of wind power equipment is mainly to reduce pollution and improve the degree of greening in the processing cycle of spare parts of metal materials and composite materials. Table 6.12 shows the major links with lower greening degree in the wind power industry at present.

In addition, attention should be paid to energy consumption, locally ecological damage, recycle and cyclic utilization that are induced in transport, installation, operation and maintenance of wind power equipment.

Regarding questions above, the greening degree of wind power equipment manufacturing is enhanced by applying new materials, enhancing the green management, adopting new technologies, etc. This is reflected as follows:

(1) Optimization of manufacture environment

The wind turbine is manufactured under a simple environment, while in the process of producing parts, especially blades, lots of FRP dust will be generated in the procedures like forming and die assembly, post-processing, and blade root processing. The workshop will be polluted by the dust, which will further affect the quality and people's health. Air blower and air removal system are combined generally in use, to form a cutting room with large amount of air. In this way, the dust sources produced in cutting, polishing, and other procedures are isolated from the workshop environment. Additionally, the automatic cutting machine with suction device is applied for cutting to reduce dust. Apart from technical means, 5S activity (Seiri, Seiton, Seiso,

Table 6.12 Recycling method comparison of fiber-reinforced plastic (FRP) waste

Type	Method	Range of application	Recycled products	Purpose	Advantages	Disadvantages
Chemical recycling	Pyrolysis	Including polluted FRP waste	Pyrolysis gas, pyrolytic oil, solid by-product	Used as the filling of fuel, new FRP, thermo-plastic plastics and for other purposes	Capable of treating polluted FRP	Complex technology, big investment and high recycling expense
Physical recycling	Crashing and pelleting	Only for unpolluted FRP waste	Crashed material	Used as FRP, plastic, coating, and paving material	Low-cost, simple treatment and directly used crashed material	The polluted FRP is cleaned by type
Energy recycling	Incinerating	Only for waste or plastic with higher resin content	Heat	Heat and heat source	Low-cost and simple operation	Secondary pollution for the environment

Seiketsu, and Shitsuke) is an important standardized management to optimize the manufacturing environment.

(2) Green manufacture process

In the process of producing wind turbine parts, the green manufacturing technology has been widely applied, including green emission reduction process technology, energy consumption process technology, environmental protection process technology, etc. There are successful cases for green manufacturing of wind power equipment, e.g., for the production of wind turbine blades, the open FRP hand lay-up process is comprehensively upgraded into the closed vacuum infusion process. In recent years, the automatic diversion technology is adopted by constant upgrade, to reduce the use of infused glue and auxiliary materials, and improve the surface quality of the blade. Furthermore, water heating system is used in manufacturing the blade die, to reduce the electric energy consumption, and ensure uniform heating of the die, thus lengthening the service life of the die. LM Company has transformed the heating die into the non-heating die, further decreasing the energy consumption and manufacturing cost.

In order to improve the production efficiency and processing quality, save resources, and protect environment, NC machine technology and special machining technology have been extensively adopted in manufacturing and processing parts of the wind turbine.

(3) Selection of new materials

Selecting new materials for wind turbine parts plays an important role in promoting the green manufacturing. Prepreg is commonly used in manufacturing blades. Hexply M19 new prepreg developed by Hexcel Corporation is a low prepreg, which aims at accelerating the curing rate of the current prepreg by 15–20%, and this will help reduce the energy consumption and produce more blades in a week.

In addition, American PPG Company developed an environmentally friendly protective coating, which is used for wind turbine blades and towers.

(4) Recycle and reuse

Recycle and reuse of wind power equipment can be divided into the reuse of the entire product after renovated, reuse of parts after renovated, and reuse of materials after recycled and remelted. Except for relatively complicated recycle and reuse of wind turbine blades, most other parts are easily recycled and reused, and the product cost may be reduced by about 10–30%.

According to the predication of DEWI, approximately 50,000t waste blades will be generated in 2020. Most wind turbine blades are made from FRP at present. Most of its waste are disposed by traditional landfill and incineration. This disposal method wastes a lot of land, leads to environmental pollution and cost increase; therefore, it has been a social issue and influences its further use. Each country attaches importance to recycle and reuse of FRP, and carries out relevant researches quite early, among which pyrolysis recycling and crashing recycling are economical and suitable (see Table 6.12).

Some wind turbine blade manufacturers start to study thermoplastic composites to manufacture wind turbine blades at present. Such material boats recyclable, light weight, good shock resistance, short production cycle and other merits, compared with thermosetting composites, but has a high process cost. This defect limits its application to wind turbine blades. Enterprises in some countries are developing the low-cost manufacturing technology of thermoplastic composites and engaging in the research on recycling of new FRP waste.

2. **Task and target**

Task and target of green manufacturing of wind power equipment is conducted by embracing four aspects of "promotion of energy efficiency, clean production, water conservation and pollution control, cyclic utilization" which are proposed in the green manufacturing project:

(1) Reduce the energy consumption in the manufacturing process;

A comprehensive assessment should be given to energy consumption in the manufacturing of wind turbines, which is deemed as a significant indicator of green manufacture. The energy consumption cost should be reduced by around 20% in 2020.

(2) Achieve the clean production in the manufacture of wind turbines

In the manufacturing process of wind turbine parts, the cleanliness of production conditions is assessed by the number of work hours in polluted environment, the manless production, and clean production equipment like dust removal device and air conditioner are applied. Work hours of the non-clean production will reduce by about 50% in 2020.

(3) Lessen the pollutant discharge in the manufacturing process

In the manufacturing process of wind turbines, pollutant discharge mainly comes from dust, waste water, and waste liquid in processing metal composite materials. In this regard, there is no valid single assessment means at home and abroad, and the total amount of pollutant discharge is still used as the main index (reducing this index by about 30%).

(4) Enhance the cyclic utilization rate of wind turbine related materials

This means to study the recycling technology of important parts after the wind turbine is out of service, and improve the cyclic utilization rate of the wind turbine. Materials recycled include the metal structure. For those with service life failing to reach the designed life, remanufacturing is adopted to study the secondary use method. The assessment method on the wind turbine life is studied to prolong the service time of wind turbines. The recycle and reuse technology is researched for composites, to improve the recycling problems caused after lots of blades are out of service.

Through above efforts, the overall target of the green manufacturing of the wind turbine before 2020 involves: reducing the energy consumption in main production links by 20%, work hours of the non-clean production by 50%, pollutants generated by 30%, and bringing the recyclable rate of raw material grade to 50%. In 2025, the energy consumption, work hours of non-clean production (compared with 2015), and generated pollutant are further reduced by 20%, the recyclable rate of raw material grade and parts grade out of service reach 80 and 20%, respectively.

In energy- and water-saving, emission, and pollutant reduction, four quantitative indexes should be observed, that is, in 2020 and 2025, the energy consumption of the industrial added value in units above the designated size reduces by 18 and 34%, respectively, compared with that by the end of the 12th Five-Year Plan; the carbon dioxide emission of the unit's industrial added value decreases by 22 and 40%, respectively; water consumption of the unit's industrial added value lowers by 23 and 41%; the comprehensive utilization ratio of industrial solid waste improves to 73 and 79%, respectively, by the end of the 12th Five-Year Plan.

3. **Ways of implementation**

In order to achieve the above-mentioned targets, great efforts should be made as follows:

(1) Establish the integrated green assessment system for the full wind power industry chain along with the green index oriented market competition mechanism.

The green standard system of the wind turbine should be set up by making a series of green assessment indexes facing specific product characteristics. This is embodied as green score in the bid and tender process of the owner, the green score is added in addition to technical and business score, indexes like factory assessment, labor protection, engineering site management are included, and the green "legislative" work is enforced on the whole.

The upstream enterprises are pushed in implementing the green manufacturing based on the green index oriented competition mechanism. The green index is used to standardize the standard mismatch caused by the lack of uniform standards for the upstream in the technical requirements during the bid and tender process. In this regard, the assessment on "three-star green buildings" and "four-star green buildings" has been carried out in such fields as green building, which promotes the industry development greatly.

Wind power parts cannot be manufactured with the uniform method because of significantly different parts types and process routes; therefore, the corresponding green manufacturing demonstration project should be built for each spare part.

(1) Break the enterprise boundary, carry our collaborative innovation and joint development, try new patterns, establish the green manufacturing service company to organize similar enterprises together for joint R&D, solving common problems, generalizing it rapidly in the industry. This process requires to deal with the win-win awareness of enterprise owners, support of capital market, permission of management system, and protection of intellectual property.
(2) Optimize the manufacture environment, introduce the green manufacturing process technology, select the new material and carry out the recycle, and reuse study on wind power equipment, so as to minimize pollution, energy consumption, and environmental damage.
(3) Combine the green and intelligent manufacture, and introduce the special manufacturing equipment, stereoscopic warehouse, and intelligent logistics equipment, to achieve automatic production, improve labor environment and product quality, reduce energy consumption and logistics cost.
(4) Establish the new industry chain layout with digital and networking technology, set up the quality and green traceability system of the industry chain based on the in-depth information sharing, and decrease the transport and logistics cost in the collaborative process of industry chain by Internet and Internet of Things.

In summary, the overall program on the wind power green manufacturing presented in this book covers five tasks, four indexes, and multiple implementation points: establishing the green index system, integrating the industry capacity, adopting energy-saving, clean production, green product design and process design and other methods, combing the green and intelligent manufacturing in the factory, transforming the green manufacturing to the green industry chain outside the factory, finally to achieve targets like energy consumption reduction, clean production, pollution control, cyclic utilization. See details in Table 6.13.

Table 6.13 Overall program on the wind power green manufacturing

	Energy consumption reduction	Clean production	Pollution control	Cyclic utilization
Green index (industrial standard)	Electric and water consumption per KW	Work hours of non-clean production of wind turbines per MW	Gas, liquid, and solid pollutant discharge and carbon discharge	Material recovery rate and part reuse rate
Green service (industrial integration)	Energy-saving renovation	Dust removal service, labor protection outsourcing service	Pollutant treatment service and carbon trading service	Material recovery service and remanufacturing service
Green process (technical means)	Energy-saving technology	Manless control and flexible manpower line	Pollutant treatment	Green product design and recovery technology
Green factory	Intelligent production, intelligent logistics, and intelligent environmental management			
Green industry chain	Industry chain network, green traceability system, industry chain space layout, and intelligent logistics			

6.8.2 *Intelligent Manufacture of Wind Power Equipments*

1. **Current status and developing trend**

The third technological renovation represented by robot, Internet of Things, cloud computing, big data, and artificial intelligence is changing the manufacturing industry. China launched the intelligent manufacturing pilot demonstration action in 2015, which is of significance in promoting the enterprise transformation. The development pattern of intelligent manufacturing involves discrete intelligent manufacturing, process intelligent manufacturing, networked collaborative manufacturing, mass customization and remote operation, and maintenance service.

Intelligent manufacturing of wind power equipment, as an important part of Made in China 2025, is a typical application of intelligent manufacturing of large energy equipment, and has the general rule of the intelligent manufacturing field. The manufacturing process of the wind turbine, as a standard discrete manufacturing process, has the characteristics of networked collaborative manufacturing due to its scattered sites, long industry chain, detailed specialization of work, as well as the characteristics of mass customization for tens of thousands of annual output and different wind turbine configurations in different wind farms. What's more, the remote operation and maintenance service pattern is used after the wind power equipment is manufactured.

There is generality and speciality in intelligent manufacturing between wind power equipment and other equipment, and its specialty mainly is shown in the following:

(1) Lower wind power cost. It is pointed out in the Renewable Energy Report published by International Energy Agency (IEA) in 2016 that the global land-based wind power cost will further decrease by 15% in 2021. During the "13th Five-Year Plan," the market price of wind turbines in China will also reduce by 20% or more, as a result, the technology upgrade is required for the entire industry. Only by improving the labor productivity, can it adapt to the change.
(2) Enhance quality standard. Compared with other mechanical equipment, the wind turbine has a longer design life of 20 years. While due to its complicated operating environment, poor maintenance, and repair conditions and high maintenance cost, its reliability mainly depends on the manufacturing quality.

With regard to the wind turbine quality, the quality standard has been adopted to define and specialize the quality information of products, the third-party evaluation system like testing and certification has been available, to implement the standard; furthermore, efforts have been made in establishing the quality monitoring, report, disclosure, and early warning system. Many traditional production techniques can't satisfy the quality requirements of products, while the reliability of products can be promoted by intelligent manufacturing.

(3) Higher individualized requirement. As the wind turbine is applied to the low-wind-speed wind farm from Class I and Class II wind area of wind resource, to special environments like high altitude, high temperature, high humidity, and high cold from the plain, a higher individualization is needed for the wind turbine. In this regard, the wind turbine should be designed in a more intelligent and detailed way. A great challenge occurs in the manufacturing process, for the R&D of customized wind turbines is required for different environmental climates. In consequence, mass customization becomes a key issue to be resolved in intelligent manufacturing of wind power equipment.
(4) Scattered operation and maintenance sites. The wind turbine is highly scattered in operation and maintenance in large mechanical equipment. For tens of thousands of wind turbines, the operation and maintenance time shall reduce by less than 5% each year in 20 years, and its operation and maintenance must be guaranteed by networking and intelligent remote operation and maintenance system.

The specialty of the wind power equipment manufacturing concerning the four aspects above triggers the following contradictions: the contradiction between large scale and lower product price, between higher quality standard and artificial production process, between mass and customization, between scattered operation and efficient operation and maintenance. It has failed the full traceability for manufacturing information during the service life of products by traditional, artificial, and visual methods, and consistent manufacture, operation and maintenance are basically required for products. For this purpose, the intelligent manufacturing is the only way for cost decrease, quality promotion, satisfaction of individualized need and distributed management.

In developing new wind turbines, the main cost is from the cost of die, special equipment, test equipment, tooling, fixture, etc., necessary for manufacturing the first wind turbine, which is as high as 50% and even 70%. In traditional wind power manufacturing enterprises, the equipment is only suitable for one type due to its insufficient flexibility and intelligence, which restricts the application of equipment and development of new products; because of insufficient flexibility, enterprises are reluctant to invest special equipment, buy would like to adopt artificial and other temporary means, which reduces the investment of intelligent equipment. The vicious cycle, coupled with short product life cycle, many varieties and small lot, results in the failure about the deserved rapid development of industry intelligent equipment and the deserved guarantee of product innovation ability.

Foreign countries push product innovation with the manufacturing process in the field of intelligent manufacturing. In the assembly plant, the wind turbine positioning production mode is converted to the flexible flow-line production. Air cushion conveyor is adopted to transfer the wind turbine from one station to another one, and there is one or multiple professional large equipment that may improve this procedure in each station. This may reduce the artificial intervention and improve product consistency. Moreover, the transfer of station makes the procedure fixed, and further fixes, improves, and optimizes the production equipment, test equipment, and logistics equipment of this procedure link.

2. Task and target

The product quality is the first target of wind power intelligent manufacturing. On this basis, the task and target of intelligent upgrade and transformation are made embracing the "product–process–equipment" and their collaborative function, according to the industry features like mass customization.

(1) Reduce artificial operation to improve the consistency of manufacturing process and products, introduce robot and other projects to achieve efficient and low-cost automatic and digital production with modern production means.
(2) Introduce relevant technologies of the intelligent manufacturing field and promote the proportion of intelligent equipment, e.g., increasing the application of manufacturing technologies to remanufacturing of wind turbine gears. This aims at that the intelligent equipment proportion exceeds the average level of other industry in 2020.
(3) Build the digital, networking, and intelligent workshop based on the production process features and technical requirements of each spare part; raise the use efficiency of the machine tool for mechanical processing intelligent workshop; accelerate logistics circulation and enhance the logistics collaborative capacity with the manufacturing executing system (MES) software for assembly intelligent workshop (Institutional Finance 2015).

(4) Create a full intelligent industry chain, improve the automation ratio of information processing, resolve the problem between mass and customization of the wind turbine; break the matching things of Internet, cloud computing, industrial big data technology by independent innovation and in-depth cooperation, realize informationized management and remote exchange while reducing travel cost, and increase the frequency of quality test and accuracy of information reflection.
(5) Establish service manufacturing industry, introduce big data center, global monitoring center, remote expert system, assets management system, and other technologies, integrate the industry intelligence by digital operation and maintenance to solve the contradiction between scattered performance and efficient maintenance of the wind turbine, and achieve the integrated innovation and engineering application of the new-generation information technology and manufacturing equipment fusion.

3. **Ways of implementation**

In order to achieve the above task and target, efforts should be made as follows:

(1) Enhance the industrial base, establish wind power industry chain process renovation and quality index system

On the one hand, create the wind power industry chain map, draw the production process route of each spare part, and put forward the target method and thought for the process improvement; on the other hand, set up the quality index system of each spare part, based on which to deduce the manufacturing requirement and intelligent manufacturing method of the spare part.

(2) Introduce intelligent equipment and promote intelligence of the manufacturing process

Expedite the introduction and industrial layout of robot; introduce welding robot, abrasive machining robot, feeding and blanking robot, mechanical arm, and other equipment in the machining enterprises; introduce assembly robot, study the relationship between robot movement and assembly position under the mass customization of wind power industry.

Develop the special equipment for the special process of the industry; develop the special assembly equipment, tooling and fixture, power assisting equipment, and enhance assembly quality based on narrow space of assembly work face inside hub and nacelle in the wind power industry; develop the special paving, infusing, gluing, bonding, cutting, polishing equipment for composite materials of the wind power blade industry, which will improve production conditions and product consistency (Su 2014). Such equipment can be developed by industry–university–research cooperation.

The flexible production line should be built for the mass and conditional place of equipment. In addition to the huge standard parts, the production line of wind power intelligent manufacturing should be designed flexibly. This involves using stereoscopic warehouse, intensive warehouse, and other intelligent warehousing means, Automatic Guided Vehicle (AGV) and other flexible transport technologies, properly combining traditional logistics automatic equipment like belt conveyor and chain conveyor, connecting the logistics system and production system with the transfer robot for automatic feeding and blanking of the production system, and creating the software defined flexible production line with Warehouse Control System (WCS) and MES software.

(3) Establish a full intelligent manufacturing system under the dominance of process route

China has complete system in manufacturing wind turbine parts. Each link should be upgraded and renovated intelligently based on the characteristics of intelligent manufacturing of different parts. Take the wind turbine blade for example, the way of intelligent upgrade and renovation for its manufacturing process is shown in Table 6.14.

In promoting the intelligence of wind turbine assembly, management of the supply chain, automation of sub-assembly and general assembly should be taken into account.

Take sub-assembly of wind turbine hub for example, the assembly material is heavy and is hardly transported without assistance; flexibility of robot and other general equipment can't meet relevant requirements due to narrow space and compact layout; assembly parts are of many varieties, including mechanical structure, sensor, motor, electric control cabinet, battery, cable, bracket, etc.; the commissioning process is complicated. Accordingly, the automatic and intelligent solutions shall be chosen for the process step one by one based on the specific conditions of products.

In the intelligence of TAMR process of the wind turbine, the wind turbine is finally assembled on site. Due to limited site conditions, the intelligent manufacturing means adopted are also restricted, and the thinking of mobile factory on site is needed. Final assembly for key parts, including torque control of screwing bolts, wind wheel assembly, hub wiring and other key process steps, is included into the intelligent manufacturing management system in a factory-based way uniformly.

Table 6.14 Way of intelligent upgrade and renovation for blade manufacturing process

No.	Blade process	Start point of intelligent manufacturing
1	Clipping of grass fiber cloth	Automatic clipping
2	Curved surface laying of grass fiber cloth	Automatic laying, process control system
3	Vacuum infusion of epoxy resin	Automatic blend compound, supporting laser designation
4	Film uncovering	Blade root, trailing-edge cutting equipment
5	Film composite	Automatic gluing and automatic thickness detection
6	Cutting and polishing	Automatic cutting and polishing robot
7	Paint spraying on surface	Automatic spraying and quality visual identification

After the wind turbine is installed, the automation of its remote operation and maintenance process, as remote operation and maintenance intelligent manufacturing, is a typical application of service manufacturing industry.

(4) Establish the industry intelligent public service platform, to change the scattered R&D pattern, centralize dominant enterprises for joint development, collaborative manufacturing and R&D issues of large wind turbines.

Few foreign experience and data can be used in developing large wind turbines, and it is far insufficient only by introducing, digesting, absorbing, and further independent innovation. The related industry chain at home and abroad is imperfect, it is highly invested in building such perfect industry chain, and only collaborative manufacturing can reduce repeated investment and relevant cost. Thus, joint R&D and compatible collaborative manufacturing may be executed by coordination between the Ministry of Science and Technology and the industry association under the leading of large wind power equipment manufacturing enterprises; furthermore, repeated construction like die may be reduced by digital design platform and digital manufacturing platform (Zhan 2014).

(5) Promote enterprises to set up the industrial big data operation and maintenance platform, intelligent wind farm monitoring platform, and predictive maintenance platform and conduct the industrial big data format standard construction.

The intelligent wind farm monitoring platform shall be capable of standard acquisition, monitoring and storage of operation and maintenance information, intelligent mobile monitoring, digital overhaul and maintenance, intelligent fault diagnosis and analysis, online health status analysis and assessment, and so on. At the same time, the big data platform can be based to analyze the operation condition of wind power projects and find out potential safety hazards of wind power projects. On this basis, the big data operation and maintenance system based on the detection and data mining technology is applied to remove hidden risks and make relevant operation and maintenance strategy. This will finally help reduce the wind power operation and maintenance cost to the ideal price range and improve power generation efficiency.

The predictive maintenance platform is available for predictive maintenance of the wind turbine based on the analysis for mass data. The future wind turbine, just like intelligent robot, may develop toward the direction of cognitive computing. As the standardization and professionalization of the wind power operation and maintenance management advance gradually, the wind power operation and maintenance service is growing toward the preventative and predictive orientation in the future.

Eventually, the full life cycle of big data platform is set up by integrating the operation, production, and design big data of the wind turbine.

(6) Construct Industry 4.0 demonstration industry for the intelligent manufacturing of full life cycle management of the wind turbine

Green manufacturing and intelligent manufacturing of wind power equipment are of strong mobilization and extensibility. The manufacturing of wind turbines is characterized by small lot, many varieties, mass customization, involves multiple disciplines and fields like machine, structure, material, electricity, composite material, meteorology. It also has higher requirements of 20 years' reliability and wide applicable range for product operation. Thus, it is a complex equipment manufacturing industry.

The green and intelligent renovation for the manufacturing process of its structural parts is of referential value for other industries; the manufacturing process of its electrical parts and subsystem has referential significance on the construction of intelligent equipment (Zhang and Han 2013); the construction of its maintenance and repair management, spare parts management, product quality traceability system is abundant and profitable experience and reference for distributed manufacturing, operation and maintenance and for the future global manufacturing layout of large equipment (Table 6.15).

Table 6.15 Blade intelligent manufacturing process

	Blade and structural parts	Wind turbine assembly	Lifting transportation	Operation and maintenance
Intelligent equipment	Blade profile polishing robot Large profile painting robot	Flexible wind turbine assembly robot	Jacking hoisting machine	Self-lifting overhaul robot Autonomous flight inspection UAV
Intelligent workshop	Blade intelligent workshop Hub intelligent workshop Tower intelligent workshop	Electrical cabinet assembly intelligent workshop Converter assembly intelligent workshop Gear case assembly intelligent workshop	Intelligent handling robot	Site maintenance mobile workshop
Intelligent factory	Blade mobile factory Tower mobile factory	Direct-drive motor mobile assembly factory	Intelligent self-dispatching robot	Remote intelligent operation and maintenance platform Intelligent fault diagnosis platform
Intelligent industry chain	Industry chain collaborative R&D/manufacturing integration digital platform		Intelligent virtual factory	Remote optimizing system
Intelligent product	Intelligent self-sensing component/intelligent self-optimizing system		Cross-platform transportation system	Remote monitoring platform

China's complete wind power manufacturing system, high nationalization and intelligent wind farm operation and maintenance present a higher requirement for the management of spare parts of the wind turbine. For the purpose of operating and maintaining the wind turbine of 20 years' service life in a better way, and obtaining timely and effective support of spare parts, wind power equipment manufacturing enterprises should possess good information-based infrastructures for the full traceability of products-technologies and establish a batch of demonstration projects. Endeavor shall be given to complete the construction of intelligent workshop demonstration project for four main parts of the wind turbine blade, gear case, generator, and converter, and the whole machine assembly intelligent workshop demonstration project in 2020.

6.8.3 Concluding Remarks

Innovation-driven wind power green and intelligent manufacturing, as an inevitable choice at a certain stage, has become the unique route of wind power industry for upgrading, transformation, and sustainable development while facing a number of challenging issues like cost reducing, quality enhancement, mass customization, scattered operation and maintenance. With its large scale and definite target, the green and intelligent manufacturing of China's innovation-driven wind power industry would keep the same step with international community.

(H. Y. Ye and L. K. Fu)

6.9 Diversified Utilization of Wind Energy

Basically, the efficient utilization of wind energy on a large scale is dependent on grid-connected wind power, which is currently restricted by inadequate grid construction and market consumption. In recent years, there were serious problems of wind curtailment in the grid-connected wind power. Under this circumstance, the concept of diversified utilization of wind energy was proposed to avoid energy waste.

6.9.1 Multi-energy Complement

1. **Background**

Multi-energy complement is an energy supply model that permits mutual conversion and transmission between various forms of energy such as electricity, heat, gas aiming at complementing each other to mitigate the imbalance between energy supply and demand, promote a virtuous circle of ecological environment, and achieve the low-carbon clean development.

There are two major modes for the multi-energy complement and integrated optimization projects (NDRC 2016): At first, the end users' demand mode such as electricity, heat, coal, and gas is to develop and complement the traditional energy sources and the renewable energy according to local conditions, optimize the layout and implement the integrated energy supply infrastructure, and realize the multi-energy coordinated supply and comprehensive cascade utilization of energy through the triple generation of natural gas heat, electricity, and coal, and the distributed renewable energy source and smart energy microgrid; secondly, the energy-base mode is to promote the construction and operation of wind, solar, hydro, thermal, and reserve multi-energy complementary systems based on the resource combinations of wind power, solar power, hydropower, coal and natural gas from the large-scale hybrid energy base.

The multi-energy complement system with integrated optimization project is an important part of the "Internet +" smart energy system, which is conducive to improving the coordination of energy supply and demand, promoting clean energy production and local consumption, and reducing curtailment of wind, solar, and hydro and power rationing, and promoting the consumption of renewable energy with the objective to enhance the overall efficiency of energy system. Therefore, it has both practical significance and far-reaching strategic significance for development and operation of building modern clean, low-carbon, safe, and efficient energy system.

2. **Working Principle**

(1) Distributed Generation in Microgrid

In the distributed energy system, distributed generation (DG) is an effective way for wind energy applications. The system capacity can vary from several kilowatts to several tens of megawatts, combining various energy sources and power including wind energy. Compared with the grid-connected wind power, distributed generation has the following advantages:

1) Supply power near the load center by utilizing the renewable energy to reduce the coal energy consumption, transmission and distribution costs, simultaneously with reduction of environmental pollution and the dependence of load on the power grid;
2) Provide various forms of energy such as typical CCHP to achieve the cascade energy utilization, and improve the overall use efficiency of energy;
3) Distributed energy system can be grid-connected or run independently, with flexible load regulation, thereby improving the reliability of power supply cooperating with the large grids. For example, the system can maintain power supply for important users in the event of power grid collapse and accidental disasters.

The diversity of distributed power sources, the dispersion of the access locations, and the intermittence and randomness of some renewable energy sources could cause technical and management difficulties to the grid connection of the distributed power supply. The microgrid, as an effective organization form of the distributed power supply, can not only give full play to the advantages of the distributed power generation technology in resource conservation and environmental protection, but also can effectively solve its technical and management difficulties in grid connection. Its basic structure is shown in Fig. 6.37.

A microgrid is a small-scale power generation and distribution system composed of a variety of distributed power supplies, energy storage systems, energy conversion devices, loads, and monitoring and protection devices. It represents an independent autonomous system that can achieve self-control, protection, and management. In addition to being operated in parallel with the grid, it can also be operated in isolated islands (Wang Chengshan etc. 2008).

In grid-connected operation, similar to the traditional distribution network that obeys the system dispatch scheduling, it can simultaneously use the distributed generation within the microgrid and draw power energy from the large power grid, and can deliver excess power to the large power grid when it has excess-sufficient power. When an external large power grid breaks down and the power is off or there are power quality problems, the microgrid can control the main breaker to cut off connection with the system environment through an energy management unit, and turn into a mode of independent operation. At this time, the microgrid can realize the efficient and safe power supply for all loads in the network. When the fault is eliminated, the large power grid can be connected again simultaneously through the self-regulation of the microgrid system.

Different countries, regions, or institutions have different focus on microgrids. They can be summarized as follows (Wang Chengshan etc. 2015):

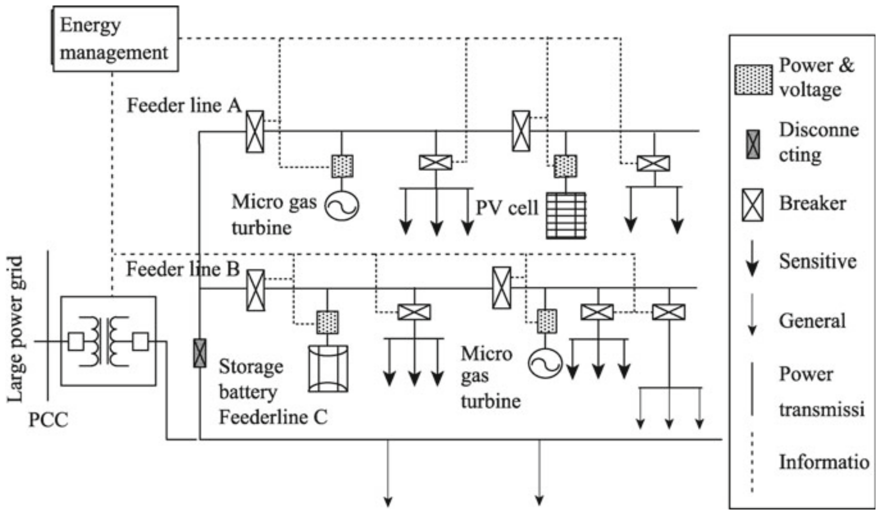

Fig. 6.37 Structure diagram of typical microgrid

1) Improve the reliability of power supply and provide support services for the power grid as a control unit by integration of the renewable distributed energy resources.
2) Build an independent microgrid systems based on local renewable and distributed energy sources for safe and reliable energy supply in remote communities, islands, military bases, and other remote areas or load-distributed areas, while avoiding the extension by construction and implementation of large power grids and protecting the environment.
3) Provide high-quality and diversified energy supply reliability services and comprehensive utilization of cooling, heating and power, increase the energy supply capability in extreme weather, and provide energy for special loads such as seawater desalination, hydrogen production by water electrolysis and remote communication base station, hybrid power supply system and building integration, wind–solar hybrid power street lamp and other municipal projects.

(2) Wind–hydro hybrid power in Hydropower base

By river cascade development, hydropower bases can own significant reservoir capacity for complementation of hydro, wind, and solar power. The reservoir can be further optimized for more flexible utilization in consideration of reservoir storage and regulation performance. The regulation capacity of the cascade reservoir group represents a giant energy storage pool, which can not only achieve daily and weekly regulation, but also realize seasonal or even annual regulation.

In the hydropower energy base, when the wind power and hydropower are jointly operated, in terms of daily scale, the hydropower can track the loads in real time and fully absorb the wind energy, and including stabilization of random wind power fluctuations according to the real-time variation in wind power generation output and by its own advantage of regulation storage and the flexibility of the unit regulation; in terms of annual scale, the hydropower stations with seasonal and annual capability for regulation of performance can regulate the imbalance of wind power during the year, give priority to the role of wind turbines, and make full use of the existing grid-connected external transmission galleries of hydropower stations to fully absorb the wind power. Increased utilization of wind power maximizes the performance and benefits of reservoir storage and regulation for optimized energy generation.

Figure 6.38 shows the basic principles of the daily complementation operation modes of the wind power and hydropower. Based on the characteristics of hydropower with rapid start/stop, flexible operation, and strong ability to track the loads, we can reduce the hydropower load when the wind power output increases, and increase the hydropower output when the wind power output decreases to keep the overall external output stable. At the same time, when the wind power output changes rapidly due to weather changes, it responds quickly to track the real-time changes in wind power output, and stabilize the power output, in order to avoid the impact of intermittent wind power output on the power grid, and ensure the stable power supply. When there is an extreme situation where the hydropower is fully loaded, all wind power is discarded and the hydropower is fully loaded according to the load demand.

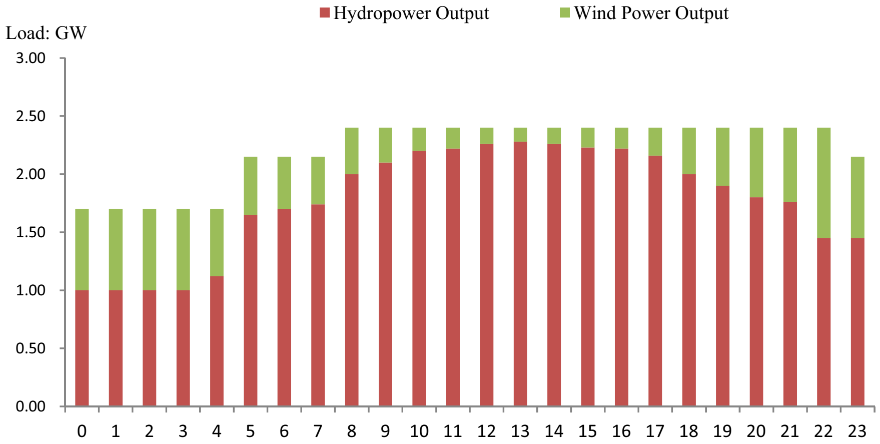

Fig. 6.38 Schematic diagram of the daily operation mode of hydropower base and the wind power complex nearby

In summary, the wind energy can be combined with a variety of other energy sources to form a hybrid power generation system. With flexible application model, the environmentally friendly and energy-efficient power utilization target can be achieved, which is one of the diversified development trends of wind energy.

(3) **Project Cases**

(1) Wind, Solar, & Diesel with Storage and Seawater Desalination Microgrid in Dongfushan Island, Zhejiang

Dongfushan Island of Zhoushan in Zhejiang Province is the easternmost island inhabited in China. There are about 300 permanent residents living on the island. Previously, the electricity for the island residents was provided by local diesel generators over a long time. Electricity supplies tended to be insufficient as electricity of this kind was expensive due to diesel transportation costs. At the same time, the domestic water on the island was mainly relied on the rainwater purified by the existing reservoirs and the water transported from Zhoushan Island. The long-term limited supply of electricity and the shortage of potable freshwater severely constrained the development of tourism economy on the island and thus adversely affected the daily life of the residents.

Considering the reality of lack of water and electricity yet good reserves of wind and solar resources on the island, an independent microgrid system with 7 × 30 kW wind power + 100 kW PV + 200 kW existing diesel generator + 960 kWh lead–acid battery energy storage system was completed in May 2011. This microgrid has been operating steadily since it was used since then to meet residence's demand. According to the on-site operation data, the penetration rate of the wind power and PV power generation is basically between 40 and 50%, which effectively reduces the diesel power generation, and greatly eases the lack of water and electricity on the island. This represents a typical case for economic develop and energy resource utilization accounting for ecological and environmental issues on the island so as to promote the island's economy and improve the quality of residents' life (Zhao Bo 2015). Figure 6.40 shows the operation of the wind and solar power reserves on site.

(2) Wind, Solar, and Hydro Hybrid Clean Energy Demonstration Base of Yalung River

The planned wind, solar, and hydro hybrid clean energy demonstration base of Yalung River is capable of mitigating the impact of fluctuation on the power grid when taking in wind and solar power by fully taking advantages of the regulation performance of the cascade hydropower stations. Their own reservoir of each station is able to play its respective role to efficiently optimize integration and generation of various resources and real-time control and dispatch the grid.

In the demonstration base of Yalung River, the hydropower output is classified into a flood season from June to October, with greater runoff and larger monthly mean output, and a dry season from November to May next year, with smaller runoff and less monthly mean output. From the month-by-month characteristics of the wind power, solar power and hydro of the demonstration base of Yalung River, as shown in Fig. 6.39, the natural complementation of the three types of energy is evidently reflected by hydropower, wind power, and PV. When the monthly mean output of the hydropower during the dry season is dropping, the monthly mean output of wind power and PV tend to rise. In contrast, when the monthly mean output of the hydropower is rising, the monthly mean output of wind power and

Fig. 6.39 Wind power, solar power, and diesel reserve and seawater desalination microgrid system on Dongfushan Island

PV tends to reduce. According to such mutual complementary characteristics of hydropower, wind power, and PV, the electricity can be bundled so as to play full roles of hydropower output galleries (Fig. 6.40).

As shown in Fig. 6.41, the daily output characteristics of wind power, solar and hydro power, the wind and PV power in the demonstration base of Yalung River

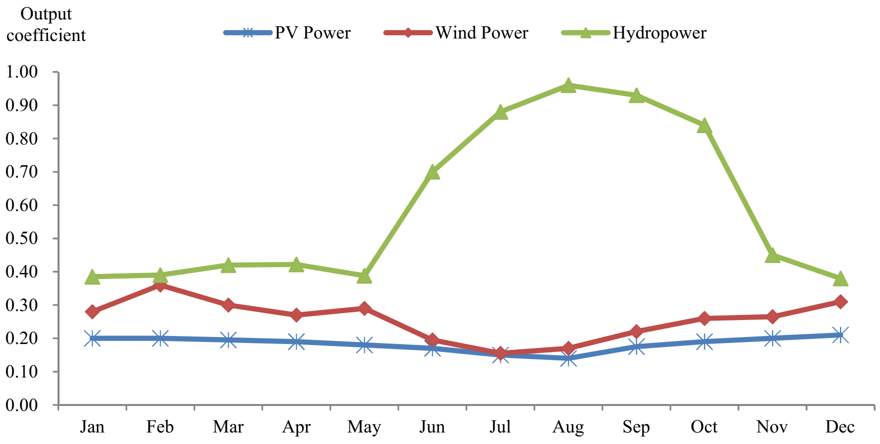

Fig. 6.40 Characteristic diagram of annual complementation of wind power, solar power, and hydro of the demonstration base of Yalung River

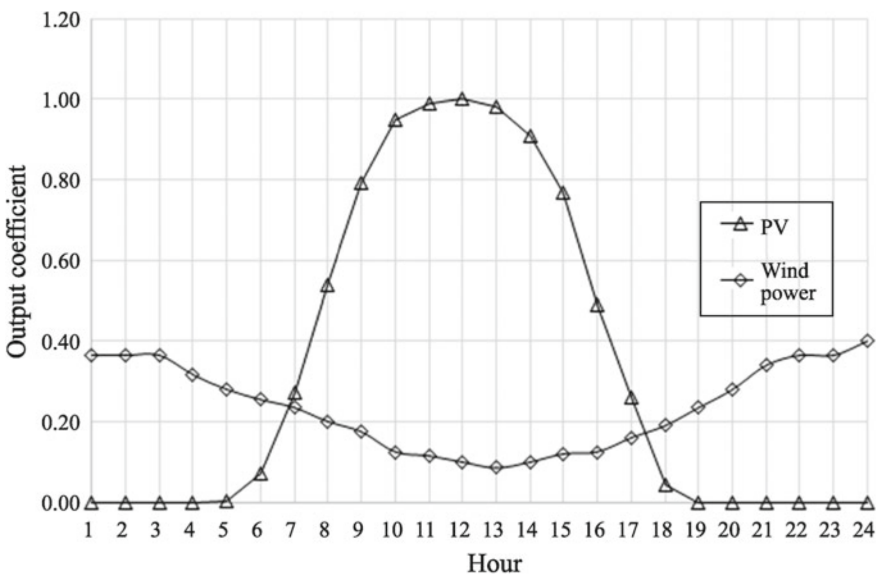

Fig. 6.41 Characteristic diagram of daily complementation of wind power, solar power, and hydro of the demonstration base of Yalung River

are complementary to each other. The wind power output is higher in the night and becomes lower at noon. On the contrary, the PV output vanishes in the night and is growing from 8:00 am to 16:00 pm. According to the daily complementary characteristics of wind power and PV, the volatility of wind power and solar power can be mitigated to some extent.

Generally speaking, when wind, solar, and hydropower are combined, the cascade reservoirs of the Yalung River exhibit outstanding annual regulation performance of long-term generation and thus resolve the imbalance in wind and solar power generation and make full use of the existing grid-connected external gallery for the hydropower stations. On the other hand, the hydropower units of the Yalung River can track the loads in real time and stabilize the random fluctuations of wind and solar power generation according to the daily real-time variations in wind power generation and solar power output including utilization of the hydropower cascade reservoir storage and regulation capabilities.

According to the characteristics of the hourly and seasonal variations in wind, solar, and hydropower, it is necessary to study the full use of the regulation performance of the completed cascade reservoirs to achieve the daily and annual complementary power generation for dispatch and scheduling of generation from various sources,, and propose daily and long-term combined dispatch, scheduling and operation mode in accordance with the stable operation of the power grid, in order to optimize the system while minimizing waste of wind and solar power resources and maximize the overall benefits. The forecast of wind power shall provide basic conditions for the real-time operation of the multi-energy complement. The most urgent issue that needs to pay attention is how to improve operational forecast of stochastic wind power generation.

4. **Perspective**

The terminal of the integrated energy supply system maximizes the overall energy efficiency and regulates the balance of heat, electricity, and cooling on the spot, and economical energy supply in a rational manner in tune with market competitiveness. The wind, solar, hydro, coal-fired, and reserve hybrid power systems are focused upon optimizing utilization of the various energy sources and resolving regional curtailment of wind, solar, and hydro power.

In the new energy-consuming areas such as new towns, new industrial parks, new large-scale public facilities (airports, stations, hospitals, schools, etc.), by strengthening the overall planning and integrated construction of terminal energy supply systems, the focus is to develop and utilize the traditional energy jointly with wind, solar, geothermal, and biomass power, and optimize the infrastructure developments such as electricity, gas, heat, cooling, and water supply pipes. Through the distributed energy and intelligent microgrid, it is possible to achieve the multi-energy complement, collaborative energy supply, and implement the energy demand-side management, promote the clean production and consumption of local energy, and improve the comprehensive energy efficiency.

In Qinghai, Gansu, Ningxia, Inner Mongolia, Sichuan, Yunnan, and Guizhou, it is feasible to take advantages of the resource combination of wind, solar, hydropower, coal-fired, and natural gas of the large-scale comprehensive energy base, and give full play to the peaking capabilities of the cascade hydropower station development within the respective drainage basin and the hydropower generation with flexible equipment including reservoir storage and regulation capabilities to build and supply energy dispatch scheduling taking into local demand and electrical supply distribution market systems, carry out the integrated operation of wind power, solar power, hydro, coal-fired, and reserve multi-energy complement systems, improve the stability of the power dispatch-output power, and improve the capacity of the power system to consume increased proportion of wind power, PV power generation, and other intermittent renewable energy sources and the comprehensive benefits.

To promote multi-energy complementary and integrated applications, innovation is necessary to consider various institutional mechanisms and business modes, implement flexible pricing and incentive policies, promote the combination of production, learning, and research, strengthen the related technical researches on overall planning, system integration, optimization operation, promotion of technological progress, and accumulate experiences, improve efficiency, and reduce costs by upgrading manufacture capacity and implementing engineering demonstration.

6.9.2 Wind Power Heat Supply

1. **Background**

During the 12th FYP, the generally balanced and locally insufficient power supply is changed to be relatively sufficient and locally excess. With the rapid development of the non-fossil energy, there are problems associated with curtailment of wind, solar, and hydro powers which are prominent in some areas. Due to inefficient local demand and in consideration of the various sources of energy generation, it is difficult to consume the wind power in the Northwest China, the North China, and the Northeast China. In local areas, the peaking capacity of the power grid is scarce, especially in the North China during the winter, which further exacerbates the contradiction of the non-fossil fuel energy consumption. During the winter, the wind curtailment rate of some wind power projects in Gansu, Ningxia, and Heilongjiang can be as high as 60%. By the immediate consequence of the wind curtailment and power rationing in local areas, there are significant economic losses in addition to cause adverse social impacts, which will seriously affect the sustainable and healthy development of the wind power industry.

The North China is rich in wind resource, especially in the winter, resulting in a significant wind power generation output. With the expansion of the wind power development in the northern regions, the conflicts between the wind power and the operation of the coal-fired cogeneration units become increasingly prominent during winter nights resulting in reduction of wind power generation which is reduced in output or even stoppage, which significant “wind curtailment.” On the one hand, the valuable clean energy is wasted; on the other hand, there is increased reliance upon coal-fired heating which resulting in serious environmental pollution and deterioration of the air quality and environment. The promotion of the clean heating technology of wind power to replace the heating resource provided by coal-fired boilers can not only really effectively utilize the wind resource, reduce the consumption of coal and other fossil energy, and but play an important role in solving the urban livelihood issues such as heat supply and the air quality control.

The Three North Regions in China, especially Inner Mongolia, Xinjiang, and Qinghai, are rich in wind resources. There is great heating demand, heating sites are scattered, resulting in conditions that are appropriate for distributed heat supply based on the renewable energy such as wind power. It is of great significance for energy supply restructuring, air pollution control, and reduction of bulk coal combustion pollutant emissions to actively develop the clean heat supply by wind power in Inner Mongolia, Xinjiang, and Qinghai.

2. Working Principle

Wind power converted to heating or heat supplies with wind power is essentially the power heating. The positive significance of the wind power heating is reflected in three aspects: energy storage, peak regulation, and emission reduction:

(1) Heating by wind power can be regarded as power generation and energy storage and utilization.

From the perspective of the entire process of power generation, transmission, heat production, and heat supply, the wind power heat supply distribution weakens the randomness and intermittency of the power generation, so the heat supply system can realize energy storage and utilization in the form of heat storage, which eases the contradiction between the discontinuity of the renewable energy power generation and the continuity and adjustability of the power demand.

(2) Heat supply with wind power can contribute to the grid load peaking.

Heat supply can be arranged through the power operation mode according to the power grid requirements and can act on the supply side and the demand side of the power grid based on the smooth output of the heat storage facilities, so as to make capacity contribution to reduce the grid load peak-valley difference and peaking.

(3) Heat supply with wind power can replace the coal burning resulting in emission reduction benefits.

The core facilities of wind power heat supply projects are electric boilers. Nowadays, the urban heating systems are mostly coal-fired and gas-fired. If the heat supply facilities with wind power are widely used in the Three North Regions, these should result a dramatic reduction in the emissions NO_x, SO_2, dust, and CO_2, which will reduce the environmental problems caused by the development and utilization of fossil fuels. This situation will result in significant environmental benefits.

Heat supply systems with wind power generally includes wind farms, power distribution equipment, electric boiler systems, thermal storage systems, heat pipe networks, and heat consumers. Considering the uncertainty of the wind power, the wind farms need to be equipped with wind power prediction systems, and the wind power heat supply systems must also be equipped with thermal storage systems and coal-fired heating boilers. The entire system needs to be rationally allocated based upon wind power forecasting to ensure the maximum use of the wind power and the normal and safe operation of the heat supply system.

The main equipment of heat supply system with wind power is the regenerative electric boiler. The regenerative electric boiler can adjust the peak and valley and reduce the valley-to-peak difference of power supply by the off-peak electricity heat storage. The heat storage system of the electric boiler is mainly divided into the resistive electric boilers, the electrode-type electric boilers, and the electric heat storage furnaces, of which the electric heat storage furnace is suitable for heat supply systems with the large-scale wind power. The high-voltage, high-power electric heat storage furnaces can operate with the voltages from 10 to 66 kV, with the unit input power of 100 MW, and the heat storage capacity of 800 MWh. The equipment should have a large capacity for energy storage and the ability to achieve the 24-h heat supply in large-scale and major large-scale urban areas.

The power grid is an important intermediate medium between the wind farm and the heat supply system. To maximize the consumption of wind power, reduce wind curtailment, meet the active demands for heating in the market, and reduce coal consumption thereby reducing carbon emissions, the power grid will need to play a role of the transmission and regulation of the power within the grid, promote the construction of the supporting power grids adapting to the development of clean heating of wind power, study and prepare the electric power operation and management measures adapted to support clean heating of wind power to ensure the reliable operation of clean heating project using of wind power. Figure 6.42 shows the working principle of the heating station.

3. **Project Cases**

For the wind power heat supply mode, the wind power output during the wind curtailment period can be fully used to increase the grid-connected power of wind farms, and alleviate the aggravated emissions of atmospheric pollutant caused by

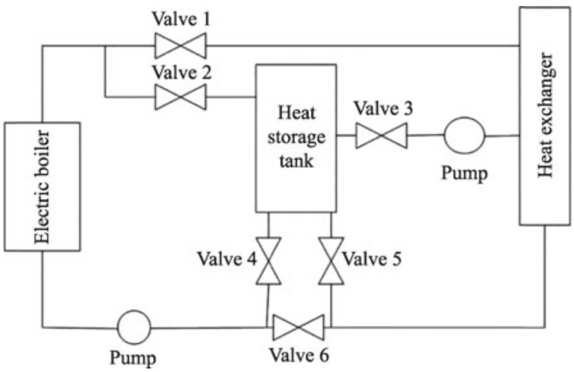

Fig. 6.42 Working principle of heating station

coal-fired power plants. In Inner Mongolia Autonomous Region, which represents as the largest demonstration project base for heat supply with wind power in China, nine demonstration projects for heat supply with wind power have been constructed in five banners/counties including Chahar Right Middle Banner and Siziwang Banner in Ulanqab, Balinzuo Banner and Linxi County in Chifeng, and Jarud Banner in Tongliao, with wind power heating area over an area of 1.6 million m^2, and wind power consumption of 250 GWh during the heating period.

The Siziwang Banner heat supply project with wind power (Wang Jianqiang 2014) is located in Jishengtai Township, Siziwang Banner, Ulanqab, about 120 km away from Hohhot. The heating station is located in the Fukang Community in the northwest of Ulan Huar, where the government of Siziwang Banner is located, and it covers an area of 6277 m^2. The construction scale of the wind farm is 200 MW with 100 wind turbines each 2 MW capacity. The heating capacity of the heating station is 500,000 m^2, and 24 resistive electric boilers with capacity of 2.16 MW for a total capacity of 51.84 MW.

The operation modes of electric boilers can be operated during low demand load periods of power grid and the operation in peak load period of power grid. During low load period of power grid, the electric boiler is started to heat 70 °C backwater to 130 °C outlet water. Part of outlet water is delivered to the heat exchange station for heat exchange and then the heat is supplied for heat consumers, the other part of the outlet water is delivered to the heat storage device for storage. During peak load operational period of the power grid, the electric boiler is closed, and the heat storage device supplies heat independently. The high-temperature hot water stored in the heat storage device is delivered to the heat exchange station through the primary pipe network to supply heat to the heat consumer. Normally, in the winter, the electric boiler works for 13 h every day from 18:00 to 8:00, the next day, while the heat storage tank works for 11 h every day from 8:00 to 18:00.

4. Development Prospect

In the regions with severe wind curtailment and power rationing, heat supply with wind power can stimulate the power consumption on the demand side, relieve the pressure on power grid transmission, play a role in adjusting the peak and low load for the power grid, enhance the reliability of safe operation of the power grid; at the same time, the conventional coal-fired boilers are replaced. Thus, a reduction can be achieved with respect to pollutant emissions and contribute to energy conservation and emission reduction.

For the clean heating using wind power, it is needed to carefully analyze and summarize the heating conditions in each region during winter, study the feasibility of clean heating with wind power at night during winter. The relevant work needs to be carried out according to the local conditions, the characteristics of wind resource, wind power grid demand-consumption, local grid load characteristics, and peak-to-valley feed-in tariff. The following issues still need to be further studied:

(1) The objective of the clean heating project using wind power is to replace the existing coal-fired small boilers, and to fulfill the heating demands in the areas

inaccessible to centralized areas, heat supply distribution piping network or the natural gas pipeline network, and to encourage wind farms and power consumers to take the mode of direct dealing for power supply.

(2) In principle, clean heating project Layout using wind power is to solve the problem of wind curtailment and power rationing in the existing wind power project, so it is necessary to control the scale of the new wind power project for clean heating of wind power.

(3) It is necessary to further deepen the electricity market reform, innovate the institutional mechanisms, and to study and explore the business model of clean heating of wind power in line with market principles.

(4) It is necessary to prepare and improve the supporting measures for clean heating of wind power, such as the coordination of wind power heating equipment and heat supply distribution piping network, the construction of supporting power grids adapted to the development of clean heating using wind power, and power operation and management measures adapted to heating using wind power, in order to ensure the reliable operation of clean heating of wind power.

6.9.3 Wind-Powered Hydrogen Production

1. **Background**

Hydrogen is a colorless, non-toxic, and odorless gas that can be used as a clean fuel and energy source, as well as an important raw material for chemical synthesis. There are three main methods for producing hydrogen in industry: The first is hydrogen production by water electrolysis; the second is hydrogen production by conversion of fossil fuels, including hydrogen production by reforming of natural gas and vapor and hydrogen production by coal gasification; the third is pressure swing adsorption (PSA) of other hydrogen-bearing tails gas or hydrogen production by membrane separation. Each type of hydrogen production method has its own applicable conditions and technical and economic feasibility. The hydrogen production by water electrolysis is widely used and is an important method for hydrogen production. The production process can be interrupted and can be adjusted within a certain range, such as load demand control. Load characteristics are similar to that seawater desalination. Therefore, for the hydrogen production by water electrolysis, the intermittent renewable energy sources such as wind power and PV can be used for dispatch output, and the electric power during the valley period of power grid load can be used to solve the problem of wind power consumption during this period. At the same time, the hydrogen can be produced by wind power locally to reduce the long-distance transmission of large-scale wind power, and promote the development and technological innovation of hydrogen energy.

The hydrogen production with wind power accords with the new energy industry policy, to improve the utilization of wind power and reduce the cost of hydrogen production. Hydrogen production is associated with good economic, social, and environmental benefits. At present, the developed countries such as the USA, Germany, and Japan are all actively promoting the hydrogen production by wind power. There are several demonstration projects in China both planned and under construction.

2. **Working Principle**

The system of hydrogen production by water electrolysis consists of water complementary system, lye circulation system, electrolysis cell, gas–liquid separation device, and hydrogen purification device. The process of hydrogen production by electrolysis water is shown in Fig. 6.43.

The investment, operation and maintenance costs associated with hydrogen production by electrolysis water is relatively fixed, but the cost of electricity consumed in hydrogen production, the market and selling price of hydrogen products are vary for different projects. The variation can have a great impact on the overall economic performance of the project. There are four methods for hydrogen production from wind power as follows:

(1) The hydrogen is produced in the vicinity of wind farms, and the hydrogen is directly used locally for coal chemical industry, etc.;
(2) The hydrogen is produced in the vicinity of wind farms and transported to the market in a certain area through the pipeline or storage tank, and then used for industrial production;
(3) The hydrogen is produced in the vicinity of wind farms, and the hydrogen produced is connected to the local natural gas pipelines.
(4) The hydrogen is produced in by wind power on the demand side of the hydrogen market, and the hydrogen is used locally;

Obviously, different hydrogen consumption markets determine how hydrogen is stored, transported, and used, and further determine the economic viability of the entire project. According to the different transportation methods and the end users, there are three ways of transportation: hydrogen storage containers, new hydrogen

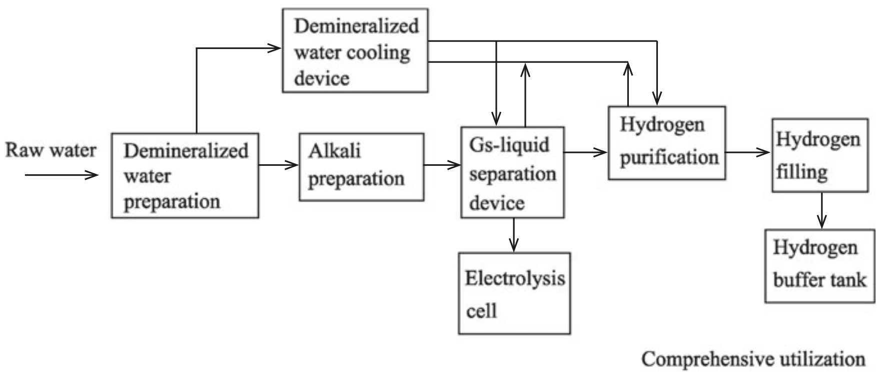

Fig. 6.43 Process of hydrogen production by water electrolysis

pipelines, and the existing natural gas pipelines. The methods of compressed hydrogen storage and liquid hydrogen storage are relatively simple and straightforward, the technology is mature, and transportation is flexible, but the transportation scale is limited and transportation efficiency is generally low. The investment cost of hydrogen pipeline transportation is high, which is 50–80% higher than the cost of natural gas pipelines resulting in relatively higher cost of the hydrogen, so it is generally only suitable for larger-scale hydrogen transportation and terminals of large-scale petrochemical and fertilizer industries with large hydrogen consumption. For the hydrogen transportation through the existing natural gas pipeline, the pipeline can be fully used. The natural gas and the hydrogen are mixed by the appropriate proportion and then delivered to all terminals that have been completed. The cost of the new natural gas pipeline is less than 50% that of hydrogen pipeline, and it can meet the needs of demand terminals for large-scale hydrogen production.

Figure 6.44 shows the hydrogen production with wind power and the comprehensive utilization of natural gas. In the existing power grid system, by using the curtailed wind power, the hydrogen is produced by the electrolysis of water and is mixed with the natural gas in appropriate proportion to provide the natural gas with hydrogen for vehicles or for delivery to other hydrogen-demanded markets. The hydrogen can also be produced by off-grid wind power, where the intermittent wind power output is combined with the hydrogen production load characteristics. Wind power output is used locally, and the hydrogen is produced by the electrolysis water in the mode of self-production and self-use.

3. **Project Cases**

(1) Demonstration Project of Comprehensive Utilization of Hydrogen Production with Wind Power in Guyuan Province, Hebei Province.

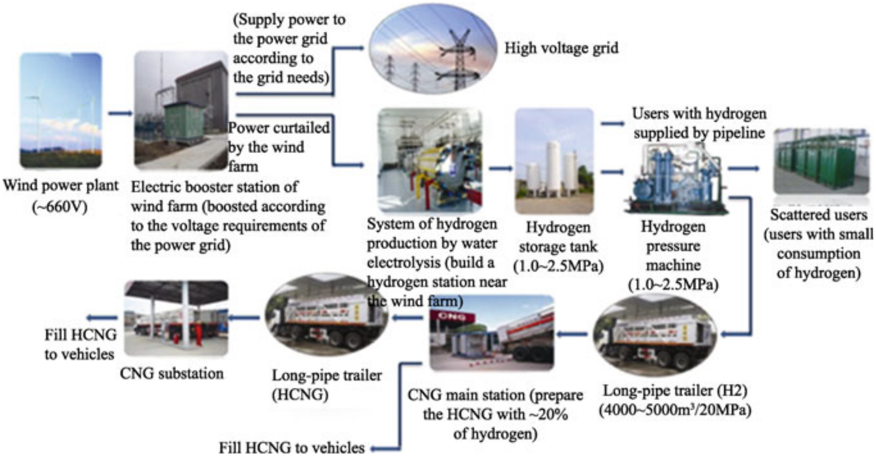

Fig. 6.44 Hydrogen production through water electrolysis and comprehensive utilization system of natural gas with hydrogen

The Guyuan demonstration project of comprehensive utilization of hydrogen production with wind power is located in Zhangjiakou Hebei Province. The goal is to build a demonstration project for comprehensive utilization of hydrogen production by wind power. The construction content includes the construction of a new 200 MW wind farm (100 sets of 2 MW wind turbine generators), a 10 MW system of hydrogen production to be used for electrolysis of water, in combination with comprehensive utilization system of hydrogen through extension of the original substation (220 kV substation) in the same period.

For the project, the electricity generated by the wind turbine is boosted to 35 kV, and then collected by the electrical circuit and connected to the 35 kV bus of the booster station of the wind farm, and finally boosted to 220 kV through the main transformer before being delivered to the power grid. When the wind is curtailed and power is rationed, the hydrogen production station is powered by the 35 kV one-circuit outlet of the booster station to produce hydrogen by electrolysis. The area of the demonstration project is rich in ground water, consisting of bedrock fissures in the mountainous area.

The hydrogen gas with a pressure of 2 MPa after purification withdraws from the hydrogen buffer tank of the plant and directed into a compressor for compression. The compression pressure is 20 MPa. The compressed hydrogen gas can be divided into two parts, part of which is directly charged to the long-pipe hydrogen transportation trailer through the branch pipe outside the compressor plant, while the other part is delivered to the changing platform in the bottling room and charged into the 40L hydrogen gas cylinders. The hydrogen in the long-pipe hydrogen trailer is directly transported outward, and the 40 L hydrogen gas cylinders are loaded into the containers and then transported outward by truck.

The 10 MW hydrogen production station is expected to consume about 35.06 GWh of wind curtailment power annually, with the converted full-load operating hours of 3504. The estimated annual wind curtailment power available at the hydrogen production station is equivalent to the increased full loaded operating hours of 175.

(2) The Project of Hydrogen Production with Wind Power in Changling, Songyuan, Jinlin

The Changling project for hydrogen production with wind power in Songyuan, Jinlin Province, is built to solve the large-scale wind curtailment of wind farms in Jilin and fulfill the needs of urban energy supply in Changling. The construction content includes the construction of a new 200 MW wind farm (132 units of 1.5 MW wind turbine generators), two units for hydrogen production by water electrolysis with capacity of 400 Nm^3/h, and the system of comprehensive utilization of hydrogen.

The total area of the hydrogen production station is 1.27 hm^2. The project is equipped with two units for hydrogen production by alkaline water electrolysis with capacity of 400 Nm^3/h, and the hydrogen is produced by the wind curtailment power of the Phase I 100 MW wind farm. The maximum electricity load is 5 MW, which is 5% of the maximum power of the proposed 200 MW wind farm. The external power for hydrogen production is supplied from a booster station at the proposed wind farm and is transmitted to the substation of the hydrogen production station through the 10 kV overhead power line, then converted by transformation to 380 V AC. The hydrogen production station is provided with two electrolytic cells, and the rated capacity of each electrolytic cell for hydrogen production is 400 Nm^3/h, where DC with a voltage of 274 V and a current of 6600 A is used which is obtained by commutating the 380 V three-phase AC through a rectifier. The hydrogen produced by the hydrogen production station flows into the hydrogen mixing station within the area of the hydrogen production station and is mixed with natural gas on predetermined proportion and then exported through the gas dispenser. It can also be transported and sold through the special long-pipe transportation trailers. The oxygen, the by-product produced during hydrogen production, is exported in bottles.

When the hydrogen is produced by the wind curtailment power of the proposed Phase I 100 MW wind farm, about 13.2 GWh of wind curtailment power can be recycled annually, which accounts for 25.38% of the wind curtailment power of the Phase I 100 MW wind farm, equivalent to 1800 h of the grid-connected utilization hours, and 132 equivalent utilization hours of the wind farm can be increased.

4. **Development Prospect**

Hydrogen production with wind power makes full use of the adjustable and controllable characteristics of the hydrogen production process by electrolyzed water. Hydrogen production improves the utilization rate of wind power and reduces the cost of hydrogen production. However, the most critical factor in the economical efficiency of hydrogen production by wind power is the hydrogen market, and therefore, it is necessary to select the production areas with high limited power and a certain hydrogen market demand. Meanwhile, the technological maturity and economical efficiency of hydrogen production from electrolyzed water needs further refinement and improved. The related market supporting policies for the storage and transportation of hydrogen and the access of hydrogen to the municipal pipeline network will also need further improvement.

In order to realize industrialization of hydrogen production with wind power, it will be necessary to follow the principle of suitable measures to local conditions, pilot operations, and gradual development. At the current stage, it is necessary to do preliminary work such as market demand research, technical economic feasibility assessment, policy feasibility in addition to examples of demonstration research of hydrogen production by wind power in areas where there is with the serious wind curtailment or limited power but where hydrogen market demand can provide the necessary foundation for a healthy and orderly development of the wind power industry.

6.9.4 Wind Power Storage

1. **Background**

It is difficult to store the electricity on a large scale. Electricity production, transmission, and consumption are completed at the same time almost instantaneously. Therefore, it is necessary to balance the power generation and load in real time to obtain the adequacy and stability required of the conventional electric power system. Renewable energy, such as wind and solar power, has great instable and variability which is reflected in the impact of standby access of systems, balance of electric power, peaking and frequency modulation, and network constraint on the reliability of the power grid. Large-scale wind power consumption represents a global-universal problem. The operation of the power system can fundamentally adapt with the availability of sufficient energy storage devices. The energy storage separates the power generation and the power utilization from time and space. Thus, power generated by the power supply is no longer required be transmitted immediately. It is not necessary to balance the power utilization and the power generation in real time. With the future development direction of the power grid, the smart grid adopts energy storage devices to perform the peaking of the power grid in order to increase the capacity of transmission and distribution systems and optimize efficiency. The energy storage technology can be widely used in power generation, transmission, distribution, and utilization of the entire power industry. Energy storage systems can improve the ability of the power system to absorb the wind power.

Wind power storage refers to the construction of energy storage devices near wind farms that are developed in a concentrated manner. Wind power is stored and reused to obtain more stable power output, increase the grid connection proportion, and enhance the adaptability of power grid and coordination with the load demand. When the wind is strong, in addition to providing the required electricity to the power load demand through the wind turbine generator, the surplus wind power is converted into other forms of energy which can be stored in energy storage devices. When the wind is weak or there is no wind, the energy stored in the energy devices is released and converted into the electricity to supply power to the load. The energy storage device is an effective measure to smooth the wind power output to the grid and improve the schedulability of the output of wind farms.

Wind power storage can be classified as mechanical energy storage, electromagnetic energy storage, and electrochemical energy storage. The mechanical energy storage includes pumped storage, compressed air energy storage, flywheel energy storage, etc. The electromagnetic energy storage includes superconducting coil, super capacitor, etc. The electrochemical energy storage includes lead–acid battery, lithium-ion battery, and sodium–sulfur battery. In the power system, various types of energy storage technologies have their own applicable situations. The energy storage methods in the wind power systems mainly include pumped storage, battery storage, and compressed air storage. At present, except pumped storage, other energy storage technologies have limited energy storage capacity, low efficiency, and high cost, and have not yet been universally applied. Table 6.16 compares various types of energy storage technologies for wind power.

Table 6.16 Comparison of various wind power or Energy storage technologies for wind energy

Energy storage type		Typical power type	Typical energy	Advantage	Disadvantage	Application
Mechanical energy storage	Pumped storage	100–2000 MW	4–10 h	Large capacity, high power, and low cost	Special site requirement	Load regulation and frequency control
	Compressed air energy storage	100–300 MW	6–20 h	Same as above	Special site requirement, gas required	Peaking power plant and standby power supply of system
		10–50 MW	1–4 h	Same as above	Same as above	Peaking
	Flywheel energy storage	5 kW–1.5 MW	15 s–15 min	Large capacity	Low energy density	Peaking, frequency control, section, and stability of power transmission and distribution system
Electromagnetic energy storage	Super capacitor	1–100 kW	5 s–5 min	Long life and high efficiency	Low energy density	Electricity quality regulation
	Superconducting magnetic energy storage	10 kW–1 MW	1 s–1 min	Large capacity	Low energy density High manufacturing cost	Electricity quality regulation and power transmission stability
Electrochemical energy storage	Sodium–sulfur battery	kW–MW	Min-hour	Large capacity, high efficiency, and high energy density	High manufacturing cost Security concerns	Various applications
	Lead–acid battery	1 kW–50 MW	1 min–3 h	Low investment	Short life	Electricity quality
	Lithium-ion battery	100 kW–100 MW	1–20 h	Large capacity and long life	Low energy density	Electricity quality, reliability, and renewable energy integration

2. **Working Principle**

(1) Pumped Storage

At present, pumped storage is a mature energy storage technology with the largest scale of energy storage global application, the most flexible operation dispatch-scheduling mode and the widest application in the power system. It has significant advantages in terms of emergency response and adapting to load changes, and has the functions of peaking, base load operation, frequency modulation, phase modulation and emergency reserve, and the unique effects on the stable operation and economic operation of the power grid. For appropriate-scale pumped storage power stations set in the areas with the dense wind power, water potential energy can be converted to electrical energy through upper and lower reservoirs and pumped storage units, so as to fully give play to the complementarity of pumped storage and wind power operation, transform the uncontrollable electricity generated by wind energy into stable electricity that can be accepted by the power grid, play a role of peaking and base load option, maintain the stability of power transmission in the power grid, especially in high-voltage power transmission grid, and improve the economic efficiency of transmission lines. When a pumped storage power station complements a large-scale wind farms, it is possible to significantly increase the level of safe and stable operation of the power grid, increase the capacity of the power grid to accept the wind power, and solve the practical problems of the delivery difficulties of wind power.

As the water head differences between the upper and lower reservoirs and the adjustable storage capacities, the storage capacities of pumped storage power stations are different, and the storage energy time can range from several hours to several days, or even up to a week or more. The pumped storage power station is currently the only energy storage facility with a storage capacity of "GW and GWh" level. The conversion efficiency is high with overall efficiency up to 75–80%. Pumped storage represents a well-known and developed global energy storage system.

(2) Electrochemical Energy Storage

The electrochemical energy storage means that the charging and discharging are conducted with the oxidation and reduction reaction of the positive and negative electrodes. It is generally composed of a battery, DC-AC inverter, control devices, and the auxiliary equipment (safety and environmental protection equipment). At present, the battery energy storage systems are most widely used in small distributed power generation. According to the different chemicals used, the batteries can be divided into lithium-ion batteries, lead–acid batteries, sodium–sulfur (NaS) batteries, and flow batteries. Figure 6.45 is a schematic diagram of a wind power storage battery.

Among the common electrochemical energy storage systems, the lithium-ion batteries mainly rely upon the insertion and desorbing of lithium ions between positive and negative electrodes to store and release energy which has characteristics such as high energy efficiency, high energy density, excellent storage performance, but smaller monomer capacities. At the megawatt and large-scale battery energy storage

Fig. 6.45 Schematic diagram of wind power storage battery

applications, in order to achieve a certain level of voltage, power, and energy level, the lithium batteries need to be used in series and in parallel. The batteries in series can increase the voltage at the output end of the battery. The batteries in parallel can double the capacity of the battery pack.

In recent years, the large-capacity lithium battery energy storage systems have been better used in the power system fields. Lead–acid battery technology is mature, and the dynamic adjustment process is very short. It can be switched between charging and discharging in a very short time. The cost is low, the application is more extensive, but the service life is much shorter, and there is a certain degree of environmental pollution during production and usage. The sodium–sulfur battery is a high-temperature energy storage battery that is charged and discharged at a temperature of about 300 °C. The active material in negative electrode is metallic sodium, and the active material in positive electrode is liquid sulfur. It has been successfully used for power system peaking and operation for base load, emergency power supply, wind power generation and stable output of other renewable energy sources, and improving power quality (Fig. 6.46).

Global, there are already hundreds of sodium–sulfur battery energy storage stations in operation, and engineering experience knowledge and experience have been developed. All-vanadium redox flow batteries are the mainstream of liquid-flow battery technology. It has the advantages of long life, independent design for energy and power, easy adjustment, and recyclability of the electrolyte.

Fig. 6.46 PV power generation system of demonstration project of storage and transmission of wind power and solar power in Zhangbei

3 Project Cases

(1) Zhangbei Demonstration Project of Storage and Transmission of Wind Power and Solar Power in Hebei Province.

The demonstration project of energy storage for wind and solar power has been built in Zhangbei Wind Farm in Hebei Province (Gao Mingjie et al. 2013). The first-phase project consists of 98.5 MW of wind power, 40 MW of solar PV, and 20 MW of electrochemical energy storage. A 220 kV smart substation is supported. Since December 25, 2011, the energy storage power station has been operated stably and safely, and it has produced 32.30 GWh. The energy conversion efficiency is approximately 89%. After near five years of operation, it shows that the energy storage system can meet the control and scheduling requirements on the monitoring system of the energy storage power plant, including achievement of a number of advanced application functions such as smooth output, planned tracking power generation, participation of system frequency modulation, and peaking and operating for base load. The energy storage systems can improve the predictability, controllability, and schedulability of power generation of wind–PV power plants. Figure 6.47 shows the PV power generation array site of the pilot/demonstration project of storage and transmission of wind and solar power in Zhangbei.

(2) Flow battery energy storage pilot/demonstration power station of Woniushi Wind Farm in Liaoning

The flow battery energy storage pilot/demonstration power station of Woniushi Wind Farm in Liaoning was completed in February 2013. It is equipped with the 5 MW/10 MWh vanadium flow battery energy storage system, including energy storage device, power grid access system, central control system, wind power prediction system, energy management system, automatic scheduling interface of power grid, environment control unit, etc. The 350 kW modular design is used by this system. The rated output power of a single electric pile is 22 kW. The capacity of this power station exceeds the 4 MW $\times$ 1.5 h energy storage power station of Sumitomo Electric in Hokkaido, and it has become the largest energy storage power station in the world with all-vanadium liquid flows as the energy storage medium.

4. **Development Prospect**

Due to large-scale access of renewable energy to the power grid, energy storage will become an indispensable and important device in the future power system in order to meet the needs of peak load shifting, valley load filling, and microgrid development.

The application of energy storage systems considers the factors, such as energy density, power density, conversion efficiency, longevity, economy, safety, and response time. Various energy storage technologies have their own characteristics and suitable applications. At present, besides the relatively mature pumped storage, other energy storage methods in technologies and economical efficiency really need further development and improvement.

The future development tendency mainly includes the following points:

(1) Conduct application demand analysis and trend assessment research on the energy storage technologies for future power system. Propose need assessments of energy storage scale, application scenario, technical indicator, and operating mode of the power grid in the future, and give the needs and development trends of storage technologies for the power system in the future.
(2) Conduct the research on the basic theories and key technologies of the power system with large-scale energy storage, including the research on the modeling, simulation, system analysis, operation control, and planning of large-scale and diverse energy storage technologies in power system applications, research on the key technologies for energy storage carrier, intermediate conversion, power grid access for different application situations, the research on the applicability and evaluation technology of energy storage technology in the power system.
(3) Conduct the research on the basic theories of energy storage, key materials and components, power conversion, system integration and control, and multiple types of combined applications, including mainly solving the applicability, safety, and system management and evaluation of representation in large-scale application of batteries and supercapacitors, solving the problems of improving the efficiency and dynamic property for pumped energy storage, compressed air energy storage, heat storage, cold storage, and hydrogen production and focus on solving basic material and other scientific problems for flywheel and superconducting magnetic energy storage.

6.9.5 Wind-Powered Desalination

1. **Background**

Similar to the energy crisis and the environmental deterioration, the shortage in freshwater resources with uneven spatial and temporal distribution has also become a major global challenge. Desalination is a strategic choice and inevitable trend to handle the shortage of freshwater resources in the future.

Desalination can be divided into distillation method and the membrane method. The most commonly included are the multi-stage flash evaporation and low-temperature multi-effect evaporation. The most representative membrane method is reverse osmosis. The multi-stage flash evaporation was once developed in large scale in the Middle East and gradually replaced by energy-saving and cheap low-temperature multi-effect distillation. Recently, due to the rapid technology development, with the lower energy consumption, the higher degree of automation, reduced investment and water production cost, the reverse osmosis membrane method compares favorably with low-temperature multi-effect distillation method. Its implementation has exceeded that of the distillation method and has become the mainstream desalination technology with the largest application scales contemporarily.

Nevertheless, desalination continues to represent a high energy-consuming industry. For example, for the desalination system of the reverse osmosis membrane method, the cost of electricity consumption still accounts for about 40% of the total cost of water production. However, this desalination system can adapt to a wide range of fluctuation of input electric power and does not have unfavorable effect on the quality of the produced water or on the performances of membrane elements, and thus, it can be used as a power load with good regulation performance. A reliable and economic power supply is an important factor that restricts the development of desalination industries for areas far away from the power grid or remote seaside areas.

Based on this, the wind power, PV, and other intermittent renewable energy sources can be used to supply power to the desalination system; it can not only solve freshwater resources shortage problem, but also permit local consumption of the intermittent renewable energy resource output. The impact of intermittent output on the large power grid can be avoided, and the energy consumption and environmental pollution can be reduced.

2. **Working Principle**

Figure 6.47 is the schematic diagram of desalination system supplied by a system of wind power and solar power and storage batteries. The system includes renewable energy power generation system of wind/PV power and storage battery system, large power grid/diesel generators, and a desalination system. Each device is connected to the system AC bus through its own converter or transformer. The main load of the system is the desalination system. The load has low requirements on the reliability of electrical energy and does not require continuous supply of electrical energy and

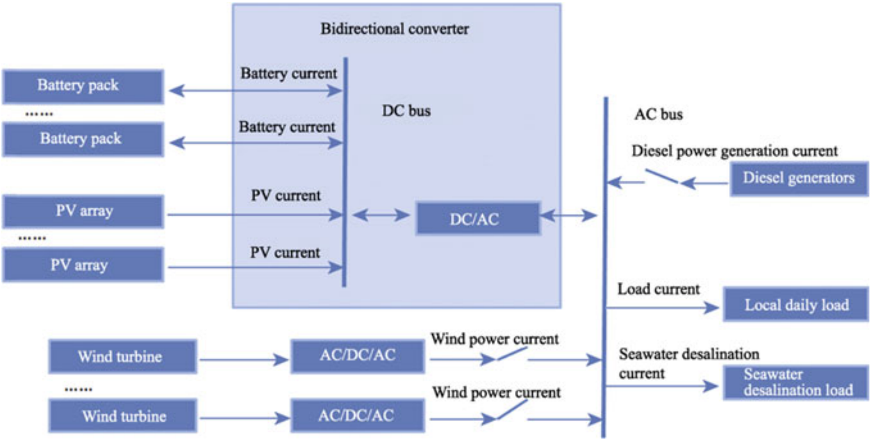

Fig. 6.47 Schematic diagram of desalination

can be adjusted within a certain range, so that the favorable conditions are created for the real-time balance between the wind power/PV output and the load demand.

For a desalination system of wind power and diesel generators, during the system operation, the desalination devices are controllable, and the number of desalination devices can be determined in real time based on the performance of wind resources. When the wind energy is strong, the load requirement of the desalination system and other loads should be met first. It is necessary to adjust and reduce the output of the diesel generator or actively limit the wind turbine output. When the wind power weakens and the maximum power output of wind turbines is reached, the system will adjust and reduce the number of operating desalination devices or make them stop operation completely, the power shortage is properly supplemented by the storage battery system and diesel generators.

On system by a system of wind power and solar power and storage batteries In the remote areas such as independent islands, an independent microgrid can be composed of diesel generator, energy storage system, wind power/PV power generation system and desalination system, which is an effective way to solve power and water utilization in the remote areas. As the electrical characteristics of desalination system are adjustable and controllable, the configuration requirements on the capacity and power of energy storage systems can be greatly reduced, and the economic type of power supply and water supply can be improved.

3. **Project Cases**

The project is located in Dafeng City, Jiangsu Province. It is the first pilot/demonstration project of the independent microgrid in China, with a daily desalinated seawater output of 1 million tons. After completion, the highest daily output of the project will be 10,000 tons. The Phase I project with the highest daily output of 5000 tons was completed and production commenced smoothly in March 2014.

Figure 6.48 shows the desalination devices of the independent microgrid system consisting of wind turbines, diesel generators, and batteries in Dafeng. The system supplies the electricity to the desalination devices with mainly wind power with supplement and diesel generators. The microgrid system includes a 2.5 MW permanent magnet direct-driven wind generator, three sets of 625 kWh lead-carbon batteries, a 1250 kV diesel generator set, and three sets of desalination devices. The main distribution voltage level of the independent microgrid system is 10 kV. Wind turbines, energy storage system, diesel generators, and desalination devices are connected to 10 kV bus through the 10 and 0.4 kV transformers, respectively. The real-time monitoring and the operation and scheduling of the entire system are realized through the microgrid energy management system.

Non-grid-connected wind power can solve the on-grid, off-grid, and wind curtailment problems, and can be directly applied to desalination. The utilization of green energy can reduce consumption of fuel for power grids and reduce the greenhouse gas emissions. It shows considerable economic benefits and social and environmental benefits. The successful construction and operation of this project represent a good demonstration for reproduction and the construction of an independent microgrid system.

4. **Development Prospect**

Desalination has become the strategic choice for solving the crisis of freshwater resources in the future. More than 100 countries and regions in the world are using the desalination technology. Since 2012, the Chinese government has successively released the policies and measures to promote the desalination industry development for making the desalination as an important supplemental and strategic reserve of water resources. The industry scale, innovation capability, and related standard systems are progressed greatly, which has laid a good foundation for the future development.

Fig. 6.48 Desalination device of independent microgrid system in Dafeng. *Source* China Jiangsu Website

In independent islands or coastal areas, it is appropriate to make seawater desalination by wind power. The application of wind power in desalination is an effective way to alleviate the shortage of freshwater in the similar regions while improving the utilization of renewable energy. In the western part of China, water has always been a major restraint to development. To promote brackish water desalination in ultrafiltration and nanofiltration, low-pressure reverse osmosis desalination projects, and coupled to desalination of renewable energy such as wind and solar energy so to ease the increasingly pressing water issue. At the same time, the western region, as an important base for renewable energy in China, can also reduce the cost of brackish water desalination by coupling desalination systems to renewable energy development.

Although the energy industry is generally optimistic about the future of the desalination market, it should be noted that there are no obvious advantages with the currently available technical economy for desalination system by wind power. On the one hand, it is necessary to comprehensively take into account the coordination issue between the intermittent renewable energy development and the management of demand side to realize the comprehensive planning and development of regional resources. On the other hand, the subsidy mechanism and policy system for seawater desalination should also be considered to support the rapid and healthy development of the industry in the early stage.

6.9.6 Concluding Remarks

Low-carbon, environmental protection and sustainability are very important goals for future power system development. As a source of clean and renewable energy, wind power will play an increasingly important role in the power grid. Development and improvement of wind power technologies will continue to expand areas of applied areas and exhibit the roles of diversified utilization of renewable energy resources. The future trends in this regard are summarized in the following.

Apply advanced technology to manufacture high quality, long life, and low cost of wind turbines including support for research and development for new wind power system including turbines which are suitable for different working conditions.

Precisely predict wind power generation and further optimize the layout of wind farms to realize the efficient utilization of wind resources and increase its market competitiveness.

Rely on advanced technologies in pumped storage station, alterative energy storage devices, distributed consumption, and smart power grid to stabilize fluctuating wind power generation and mitigate wind energy curtailment to a certain extent.

Improve energy utilization mode by promoting pilot demonstration of Hami-Zhengzhou ultra-high-voltage power transmission project, Zhangbei transmission and storage project of wind and solar power and Inner Mongolia, and Xinjiang heating supply project incorporated with wind power so as to achieve the coordinated operation of wind power, power grid, and external loads.

Make full use of renewable energy-based multi-energy complementary technologies in order to supply safe, economical, and environmentally friendly electricity to remote areas and islands, communication base stations, municipal affairs, industrial enterprises, and resident users.

In a word, the sustainable development of the wind power industry can be realized with continual in-depth research on diversified applications of wind power and breakthought of technical bottlenecks and policy construction.

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