Lowering Failure Rates and Improving Serviceability in Offshore Wind Conversion-Collection Systems

Sandeep Bala, Jiuping Pan, Debrup Das, Oscar Apeldoorn, and Stephan Ebner

***Abstract*—Reliability and maintenance are key concerns for offshore wind farms. Electrical systems are responsible for more failures than mechanical or structural systems, but they are also comparatively easier to repair. Nevertheless, it is important to lower the rate of failure and improve the ease of maintenance of electrical systems. This paper presents approaches to achieve these goals at the component level as well as at the system level. ABB's PCS6000 is used as the example to discuss component level issues. This paper also compares five possible conversion-collection system architectures considering their reliability and amenability to maintenance. The failure rates can be lowered and the serviceability can be improved by incorporating these considerations properly at the design stage.**

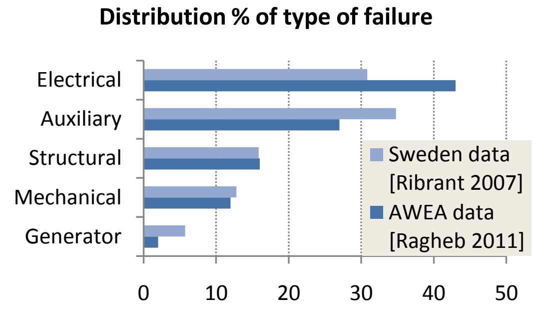
***Index Terms*—offshore wind, reliability, cluster**

I. INTRODUCTION

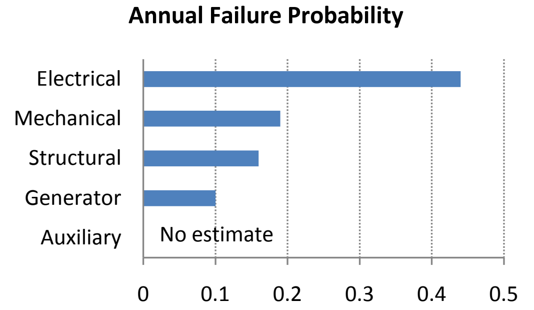
Although the first offshore wind farm was installed in 1991 – it comprised eleven 450 kW turbines located about 2.5 km off the Danish coast at Vindeby – it was not until 2007 that we began to see a sustained growth of the offshore market segment in the wind industry. Europe has been the leader in installations, already having installed nearly 4 GW of offshore capacity [1]. Now China and the United States have both assessed the viability of their offshore wind energy resources [2], [3]. China has begun building offshore wind farms, while the United States is considering building wind farms off its east coast. The offshore wind market has been dwarfed by the onshore wind market over the past 20 years, but we expect a few hundred GW of offshore wind farms to be built over the next 20 years.

There are two key differences between onshore wind farms and offshore wind farms. The first major difference is also one of the main arguments in favor of going offshore: wind flows tend to be stronger, more predictable, and more consistent offshore. Thus it is possible to harness more energy with larger turbines and to better plan the operation of the remaining other sources in the power system with which the wind farm is integrated. The second major difference is also one of the main technical challenges to ensure profitable operation of offshore farms: the operating environment of offshore farms is tougher than that of onshore farms, and the accessibility of offshore farms for maintenance is considerably more expensive than that of onshore farms. It is expensive to send crews on a helicopter or a boat to repair failures and perform scheduled maintenances, and these costs combined with the resulting lost energy production reduce the profitability of the farm. Therefore reducing failure rates and improving serviceability are greater concerns for offshore wind farms than they are for onshore farms.

Over the past 20 years the industry has accumulated many million hours of operating experience with onshore wind turbines. The distribution of the types of failures in wind turbines have been reported in several papers, for example in [4] and [5]. The results from these two references are summarized in Fig. 1(a). The figures represent the probability of the location of the failure, given that a failure has occurred. The electrical systems include the main power converter and control units, but not the electrical generator. The structural



(a) Historical distribution percentages of types of wind turbine failures [4], [5]



(b) Estimate of probability of types of wind turbine failures in a year [6]

Fig. 1. The distribution of the types of wind turbine failures

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systems include the rotor and tower structures; the mechanical systems include the gearbox, the mechanical brake, and the drive train; the auxiliary systems include the yaw system, the hydraulic system, and the various sensors. From the figure, it is clear that the electrical and auxiliary systems have historically had a higher failure rate than the mechanical parts, the structural parts, or the generator in the turbine. Based on these and other data, some researchers have estimated the absolute probabilities of failure of various components in a single turbine in a single year [6]. The medians of these estimates are shown in Fig. 1(b). The data in this graph suggest that almost every turbine will require some sort of repair every year. Once again, the estimated failure rate of the electrical system is more than those of the structural and mechanical systems combined. Since offshore winds are more consistent and have fewer gusts than onshore winds, the stresses on the structural and mechanical parts tend to be lower resulting in lower failure rates. It should, however, be noted that structural and mechanical failures result in much higher downtime and lost energy production than electrical failures.

In order to reduce the number of offshore repair and maintenance trips, the electrical system must be designed to minimize the number of failures. Previous researchers [7] have investigated the reliability of large offshore wind farm collection grids with different switching concepts. They have estimated the expected energy not served (EENS) in MWh per year for three different collection arrangements. A key observation is that the arrangement of the components in the collection grid makes a difference to the overall reliability of the system. The electrical system must be designed for quick identification of the cause of failures and for greater serviceability so as to reduce the downtime of the failed turbine or group of turbines. Thus, the reliability of the overall system is not only affected by proper design choices for the components that go into a wind turbine, but also by the choice of the overall conversion-collection system architecture itself.

The objective of this paper is to explore reliability and serviceability considerations for electrical systems in offshore wind farms from two points of view: power conversion components and power collection grid architectures. Section II discusses how to design the components in the power conversion chain. Section III compares three different options for electrical architectures. Section IV summarizes the paper and provides the conclusions of the study.

II. DESIGNING CONVERSION COMPONENTS FOR RELIABILITY

Ensuring low failure rates and improving serviceability begins at the design stage. A chain of power conversion components is only as strong as its weakest link. For the overall system to have a low failure rate, it is important that each of its components be designed for that objective.

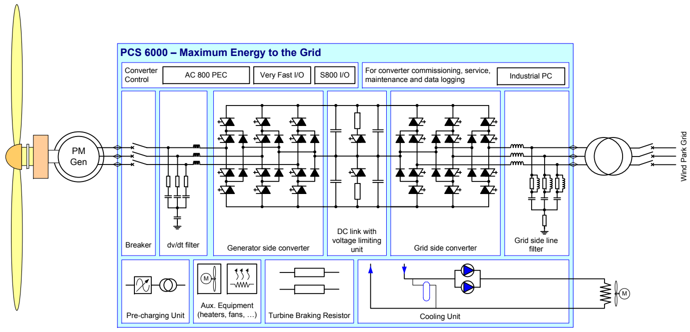


Fig. 2. The typical power conversion chain inside a tower – example using ABB's PCS6000 converter

An example of the electrical system in a typical wind turbine is shown in Fig. 2. We believe that future offshore turbines will be rated at powers greater than 3 MW. Furthermore the typical power conversion concept expected to dominate offshore turbines is the full power converter concept, either with synchronous generators or squirrel cage induction generators. Therefore the figure shows the key components in the power conversion chain, which includes:

- a generator that converts the mechanical energy from the turbine rotors into variable frequency variable voltage three-phase electrical power with a nominal voltage at around 3.3 kV ac – generation at this medium voltage level allows the use of lesser copper in the machine;
- a back-to-back three-level voltage source converter that converts the variable frequency output of the generator into a fixed dc voltage of about 5 kV dc and then inverts it to fixed frequency 3.3 kV ac – the example converter shown in the figure is the ABB's PCS6000 converter with all its attendant auxiliary subsystems, including the passive filters, the power device gate control units, the pre-charging unit, the turbine braking resistor, the heaters, the fans, the cooling unit, and the overall system controller; and
- a transformer to step-up the fixed frequency voltage to about 33 kV ac, which is the typical voltage at which power is collected within the wind farm before transmission to shore.

The rest of this section describes broadly the design considerations for offshore power converters and provides examples from the design of the PCS6000 converter. Section II-A discusses design considerations to ensure low failure. Section II-B discusses design considerations to ensure the converter is easily serviceable. Finally section II-C discusses the importance of feedback mechanisms from lab testing and field experience.

A. *Design for low failure*

1) Component choice: It should be obvious to any practicing design engineer that it is imperative to select the right high quality devices and components, and each component from each supplier must go through a rigorous qualification process before it is approved for use in the final product. Even so, there are certain fundamental design choices that can result in increased reliability of the converter.

The three most important causes of failure of semiconductor devices are voltage stress, cosmic rays, and thermal cycling. Therefore it is important to pick the right semiconductor devices in conjunction with the topology to minimize the failure rates of the converters. Previous papers [8], [9] have highlighted the advantages of the topology and devices used in the PCS6000 design. The back-to-back three-level neutral point clamped (NPC) topology is well-suited to meet the performance requirements of the application. The use of IGCTs as switching devices obviates the need to connect devices in parallel or series, because IGCTs are available in ratings of 520…5000 A and 4.5…6.5 kV. Although IGBTs are also available at similar voltages, they do not have the same current carrying capabilities. The reduced part count in an IGCT-based design results in a lower predicted failure rate. Both IGBTs as well as IGCTs are designed to minimize failures due to cosmic rays. However, IGCTs are again a better choice for the three-level NPC topology, because IGCTs are available as press-pack devices, while IGBTs are typically packaged using wire bonds. Press-pack devices have low stray inductances, which helps minimize voltage overshoots during switching. Press-pack devices are also more robust to thermal cycling and short term overloads. Thus, the IGCT-based three-level NPC converter is a sound choice for the medium voltage wind power converter.

When available, self-healing components are a good choice to improve reliability. Metallized film capacitors can be designed with insulation systems that can restore their original insulation properties after a breakdown. The PCS6000 uses such self-healing capacitors in its dc bus, making it less likely to fail.

It is important to eliminate, or at least minimize the number of, components that are more likely to fail than the rest of the system. Encoders and fuses are examples of components that tend to fail due to aging. The PCS6000 operates without any encoders, instead using software to calculate the rotor speed and torque as required. The converter also has no fuses, instead operating with advanced breaker control algorithms. Such measures help to lower the failure rate of the system.

2) Redundancies and failure tolerance: It is impossible to avoid random failures of some components. Building redundancies into the design of the converter or allowing limp modes of operation make the converter resilient to such failures, effectively reducing the failure rate of the overall system. This subsection provides two illustrations of redundancy implemented in the PCS6000.

Components on the control boards tend to have a higher failure rate than the rest of the system. Therefore it makes sense to implement either a passive redundancy (design margin) or an active redundancy (switch-over-on-failure) on these boards. In the PCS6000, passive redundancy has been implemented in the gate control unit, which has a number of capacitors in parallel so that the gate control function is not affected by failures of individual capacitors on the control board.

The PCS6000 is water-cooled, and a failure in the cooling system would reduce the power conversion capacity of the converter. Therefore it makes sense to implement an active redundancy in the cooling system. The sub-component that commonly fails is the pump, and therefore the PCS6000 has two pumps in parallel. At any given time, only one pump operates. In normal operation, the cooling system controller periodically switches between the two pumps to ensure equal aging of the two. However, in case of detection of failure of one pump, the cooling system controller completely switches over to using the good pump.

Failure tolerance is a kind of passive redundancy where the converter continues to operate with a slight impairment, even though there has been a failure of some component. For example the failure of a water flow sensor would affect the optimality of performance of the system, but it would not hamper the basic operation of the converter. Such a mode of operation is called a limp mode, and the availability of such limp modes helps reduce the failure rate of the converter.

3) Operating environment conditions: Offshore wind turbines present a challenging operating environment for power converters. The application requires the converters to operate over a wide range of ambient temperatures, typically -15°C to $+50^\circ$C. This requires a certain amount of derating of the components in the main power processing path. In addition, it requires more effective thermal design compared to that in industrial applications. The units must be tested for operation under various loading conditions, including temporary overloads as may be caused due to grid faults. The application also requires that the converter be able to withstand the humidity conditions that are present offshore. The PCS6000 enclosure is designed for an IEC ingress protection rating of IP54. This means that the converter is not susceptible to performance degradation due to dust, and that it can also withstand water splashing onto the enclosure from any angle. Finally, the subassemblies must be tested for operation under the vibration conditions that would be present in the offshore wind turbines. All in all, the operating environment requires some crucial design modifications to the power converters.

B. Design for serviceability

1) Subassemblies and their packaging: The physical arrangement of the sub-components in a converter makes a difference to the ease of serviceability. A maintenance or repair on the converter requires easy and safe access to various sub-components inside the converter enclosure. Safety of the maintenance personnel is ensured by installing an earthing switch and a de-energizing interlock on the cabinet door. Hot swap is not a requirement for offshore wind, and indeed it is not possible for certain power converter configurations. The power modules are arranged inside the cabinet in such a way that it is easy for the qualified personnel to replace them when necessary. In the case of the PCS6000, the IGCT stacks can be removed without disconnecting the bus bars or the cooling pipes. The removal merely requires discharging a spring, which normally holds the IGCTs in place, and using a service tool to separate the heat sink. All the sub-assemblies are sized in a way that a single person can transport them; the only exception to this design guideline is the line reactor, but this is also a component that is unlikely to fail. In conclusion, the ease of accessibility, replaceability, and transportability of subassemblies makes the power conversion unit more serviceable.

2) Remote operation and data logging: Since it is expensive to send maintenance personnel out to each wind turbine, it is important to have remote monitoring and remote operation

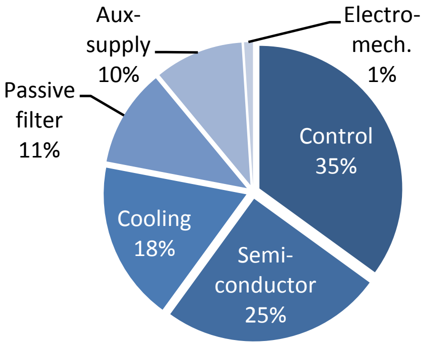


Fig. 3. Breakdown of failure rates in a typical offshore wind power converter

capability. Remote operation capabilities and a fuseless design of the power converter makes it possible to restart the system after a fault that has caused the system to trip has cleared. Remote monitoring also helps gather data about the operation of the converter, making it possible to record the performance of the system and also to record the conditions just before any significant failures. Arming the service engineers with these data enable them to take along the right replacement parts in case on-site repairs are required. Thus, remote operation and data logging help reduce maintenance trips and service time.

3) Diagnostics and condition monitoring: Maintenance can be either preventive or corrective. Corrective maintenance, of course, refers to repairs and must be carried out when necessary. Preventive maintenance can either be calendar-based or condition-based. Calendar-based maintenance is more common; once-a-year maintenance is fairly common for onshore wind turbines. But for offshore wind turbines, since maintenance visits are expensive, it may make sense to consider a condition-based maintenance schedule.

If there could be a cost-benefit from switching to a condition-based preventive maintenance schedule, it would make sense for a particular component only if the design life of the component is less than that of the overall system and if wear is the dominant cause of failure [10]. The PCS6000 is designed for a minimum 20 year life, which is the same as the overall turbine system. Some failures occur due to certain unexpected events that create operating conditions outside the design range. These types of failures cannot be averted by any kind of preventive maintenance. The science of offshore power conversion systems has not yet advanced to a level where one can count upon a condition-based maintenance schedule. The advancement of this science requires extensive operating experience and the collection of relevant data.

C. Lab testing and field experience

Once a design is complete, it must be assessed for reliability. The design engineers should be able to predict the relative failure rates of different sub-components in the power converter. As an example, for the PCS6000, this exercise yields a result like the one shown in Fig. 3. Such an exercise enables the planning of the inventory for spare parts.

Field data are essential to build proper reliability models. Sometimes the failure of a power switching device is only the final event in a chain of minor, fleeting failures. And since it is hard to foresee every eventuality during the design stage, collecting field data is important to understand the actual operating conditions of the converter. The availability of such data enables design engineers to find further possible causes for failure and then make necessary modifications to the design. Building a database of field experience is quite challenging, and it requires time and commitment from all the parties involved. The offshore wind industry is still too young for there to be a sufficient quantity of useful field data that can feed back into the design process. Until then, we must rely on best design practices for the individual components in the power conversion chain and use them in a wind farm whose electrical system is designed to be resilient to failures of individual components.

III. DESIGNING CONVERSION-COLLECTION SYSTEMS FOR RELIABILITY

The electrical system for a typical large offshore wind farm comprises wind turbines with its attendant power conversion system, a medium voltage collection grid, an offshore substation on a platform, a high voltage transmission system, and an onshore substation to interface the farm with the power grid. The collection grid typically operates at 33 kV ac. The choice of transmission system is mainly determined by the distance of the offshore wind farm from the onshore grid connection point. When the wind farm is close to the shore, high voltage ac (HVAC) transmission systems are used. In cases where the wind farm is far from shore, voltage source converter based high voltage dc (VSC-HVDC) systems have proven technically advantageous and cost-effective. In this paper, the term conversion-collection system is used to represent the internal electrical system of offshore wind farms, which includes the electrical components on wind towers, the collection cable network, and the electrical components on the transmission platform.

Offshore wind farms require huge investments and it is crucial to develop conversion-collection systems that are cost-effective, efficient, and reliable. Various system architecture design concepts have been investigated by previous researchers [11], [7] and [12]. Reference [11] discusses possible conversion-collection systems that can produce medium voltage dc power from wind turbines and describes cluster connection schemes within the wind farm. Reference [7] shows the results of a study of the reliability of large offshore wind farm collection grids by using the metric of expected energy not supplied (EENS) in MWh per year. It shows that the collection grid can be optimized from the reliability perspective by considering the network topologies and the locations and types of switching devices. Reference [12] shows the potential benefits expected from the next generation of higher voltage converters, which will be able to serve up to 15 kV ac or 24 kV dc. The study indicated that substantial energy savings can be achieved with cluster collection (with eliminated wind turbine transformers) for certain offshore wind applications.

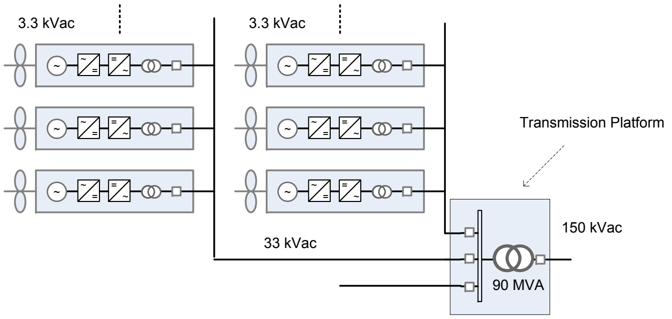


Fig. 4. A 90 MW wind farm with 33 kV ac collection grid

This section is mainly concerned with assessing the reliability of various designs for conversion-collection systems. Although one endeavors to reduce the failure rates for each of the components involved, especially the power converter system of the wind turbine, the reliability can be further improved with the choice of an optimized conversion-collection system architecture that allows for better serviceability and thus reduces the downtime during forced and maintenance outages. Section III-A describes the system architectures considered in this paper. Section III-B discusses the raw data used to estimate the reliability of the different systems. And finally Section III-C shows and discusses the results of the reliability assessment.

A. Choices of system architecture

1) Example 90 MW wind farm with 33 kV ac collection grid: The example wind farm [12] used in this paper has a total capacity of 90 MW consisting of eighteen 5 MW wind turbine generator systems (WTGs). Each high power WTG in this conventional architecture includes a step-up transformer to increase the power converter output voltage, typically at 3.3 kV ac, up to the collection grid voltage, typically at 33 kV ac. As shown in Fig. 4, the eighteen WTGs are arranged in three 33 kV ac feeders which are radial from the transmission platform. Thus, there are six WTGs connected by each feeder and the feeder power level is 30 MW. The cable length between two connected WTGs on a single feeder is assumed to be 1 km and the transmission platform is placed 1 km away from the central feeder. The other two cables run the shortest path between the feeders and the substation. The capacity factor (the ratio of the actual average power generated to the rated power) of the example wind farm is 25% which is typical for a wind farm that is close to shore.

2) System architectures without WTG transformers: Fig. 5 shows the following four system architectures without WTG transformers.

- 13.8 kVac-1: 13.8 kV ac cluster without WTG transformers
- 13.8 kVac-2: 13.8 kV ac cluster with entire electrical system on the cluster platform
- 24 kVdc-1: 24 kV dc cluster with inverters on the cluster platform
- 24 kVdc-2: 24 kV dc cluster with single inverter on the cluster platform

TABLE I
COMPONENT RELIABILITY DATA USED FOR EENS ESTIMATION

Component	Failure rate (/yr)	Repair time (hr)	Maint. rate (/yr)	Maint. time (hr)
Platform				
Main transformer	0.02	400	0.25	40
AC breaker	0.025	144	0.25	24
DC breaker	0.025	144	0.25	24
MV busbar	0.005	144		
Full power converter	0.2	144	0.5	24
DC/AC converter	0.1	96	0.5	12
Cable				
1 km MV Cable	0.015	288		
WTG (tower)				
Generator	0.1	240	0.25	24
Transformer	0.0131	240	0.25	24
AC breaker	0.025	240	0.25	24
DC breaker	0.025	240	0.25	24
Full power converter	0.2	240	0.5	24
AC/DC converter	0.1	240	0.5	12

In each of the system architectures shown in Fig. 5, the eighteen WTGs are arranged in two clusters. Thus, nine WTGs are connected to each cluster platform and the cluster power level is 45 MW. The cluster platform is located close to the middle wind tower of the cluster.

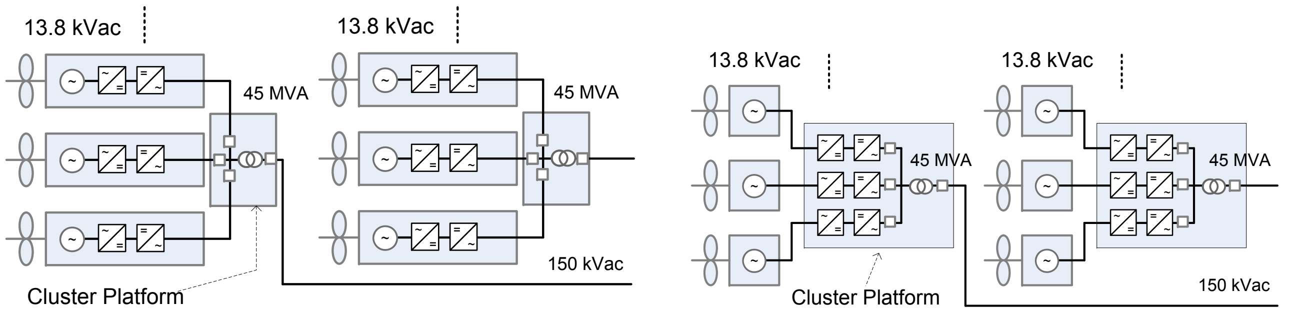
B. Reliability assessment – test data

The component reliability data used in this paper – these data are obtained from [7] and [13] – are shown in Table I. One can see that the failure rates of converters are relatively higher than those of other electrical components; they are twice those of wind turbine generators and almost an order of magnitude higher than those of circuit breakers. The failure rates are assumed to be the same for the same type of components no matter whether they are located on the wind towers or at the transmission or cluster platforms. However, the repair times of the same type of components are quite different since the accessibility to the wind towers is more limited than to the platform substation. For scheduled maintenance service, we assume there is no difference in maintenance outage hours for the components located on the wind towers and at the platform substation. The time for fault isolation and system restoration after forced component outage is assumed to be 1 hour. The maintenance outages of substation busbar and collection grid cables are not considered.

C. Reliability assessment – results

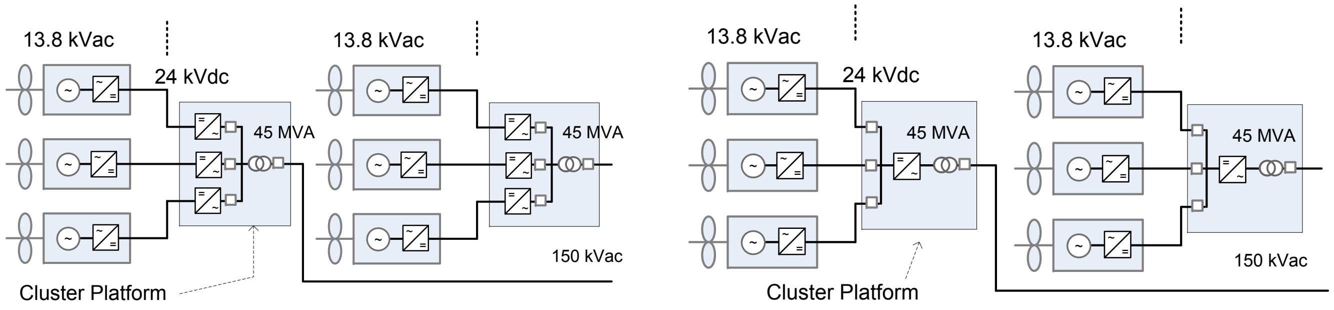
The reliability indices (EENS) were calculated for all five system architectures and the results are presented in Fig. 6. The reliability assessment considers power output loss that results from both forced outages as well as maintenance outages; overlapping events of forced outage and maintenance outage are ignored. Depending on the system architectures, the reliability indices are calculated at the following outage levels:

- Single wind turbine outage (5 MW)
- Feeder outage (30 MW)
- Cluster outage (45 MW)



(a) 13.8 kVac-1: 13.8 kV ac cluster without WTG transformers

(b) 13.8 kVac-2: 13.8 kV ac cluster with entire electrical system on cluster platform



(c) 24 kVdc-1: 24 kV dc cluster with inverters on cluster platform

(d) 24 kVdc-2: 24 kV dc cluster with single inverter on cluster platform

Fig. 5. System architectures without WTG transformers

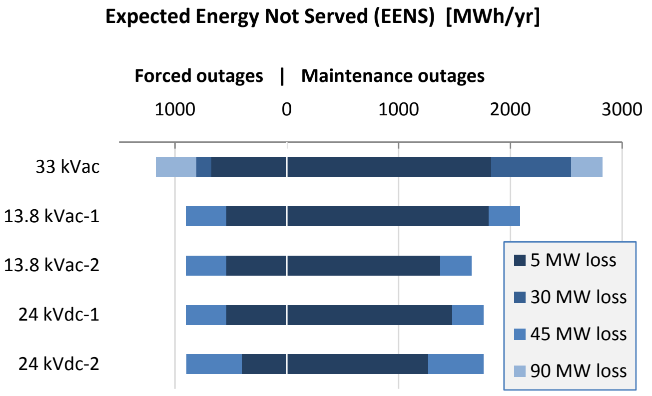


Fig. 6. Reliability metrics for different systems. A smaller value for EENS is better.

- Plant outage (90 MW)

There are three outage levels for the system architecture with conventional 33 kV ac collection grid: single WTG outage (5 MW), feeder outage (30 MW) and plant outage (90 MW). A single WTG outage is triggered by the failure of any component on the wind tower. A feeder outage is triggered by the failure of any cable section or the failure of the feeder protection circuit breaker at the platform. A plant level outage is associated with the failure of the main transformer or the busbar. The failure of a feeder protection circuit breaker also triggers a plant level outage, as the faulted circuit breaker and the affected feeder can only be isolated after shutting down the entire plant.

There are only two outage levels for the cluster-based system architectures: single wind turbine outage (5 MW) and cluster outage (45 MW). A single WTG outage is triggered by the failure of any component on the wind tower and also the failure of any component between the WTG and the common MVAC or MVDC bus on the platform. A cluster level outage is associated with the failure of the main transformer or busbar. It could also be triggered by the failure of a wind turbine protection circuit breaker at the platform. In this case, the faulted circuit breaker and also the affected WTG can only be isolated after shutting down of the entire turbine cluster.

The following observations can be obtained from the reliability assessment results presented in Fig. 6.

- The reliability of cluster connection architectures is higher than that with a conventional 33 kV ac collection grid. For the studied systems, the EENS contributed by forced outages is reduced by 26% to 41% and the EENS contributed by maintenance outages is reduced by 23%.
- The reduction of EENS in the cluster connection architectures is mainly contributed by elimination of feeder level outages (30 MW power loss) as each wind turbine is directly connected to the cluster platform with individual cable and circuit breaker (13.8 kVac-1).
- Additional reduction of EENS is contributed by the reduced repairing time of the full power converters (13.8 kVac-2) or the inverters (24 kVdc-1 and 24 kVdc-2) which are located at the platform.

Further reduction in EENS can be expected for the cluster connection architectures as the maintenance service for the components located at the platform can be performed more efficiently. For example, the maintenance service of the same type of components at the platform can be scheduled together instead of accessing each individual wind tower. If we assume the average maintenance duration for the components placed at the platform can be cut by 50% in comparison with the time required for the components at the wind towers, the total EENS contributed by maintenance outages can be reduced by more than 20%.

Fig. 6 shows that the calculated total EENS is the same for the two 24 kV dc cluster connection architectures. However, further reduction in the EENS can be expected for the 24 kVdc-2 system because the 45 MW inverter can be implemented with parallel converter modules. With such a modular converter system design, the probability of total converter failure is dramatically reduced. Thus, it is possible to reduce the EENS merely by selecting the right conversion-collection system architecture.

IV. SUMMARY AND CONCLUSIONS

The operation and maintenance costs of an offshore wind farm can be reduced by incorporating the right considerations at the design stage. Each component in the power conversion chain can be designed to reduce the probability of failure. ABB's PCS6000 wind power conversion platform has been designed with these considerations in mind. The overall farm can be configured in a way that the effect of the failure of a single component is minimized, and this requires a proper choice of the electrical architecture. Cluster architectures with ac or dc collection are examples of electrical architectures that offer better reliability indices than the conventional ac collection architecture. A cluster platform-based system allows flexible placement of wind turbine clusters in the geographical landscape. This design concept may also be considered for large offshore wind farms where the power generated by each cluster wind turbines is transmitted by a sub-transmission network to a central offshore HVAC or HVDC transmission substation. Further research is required to explore the cluster platform-based design concepts considering the minimization of the capital cost and operating cost of the overall system.

REFERENCES

[1] "The European offshore wind industry key 2011 trends and statistics." EWEA report, Jan. 2012.

[2] "2010 China wind power outlook." Chinese Renewable Energy Industries Association (CREIA) report, Oct. 2010.

[3] "Large-scale offshore wind power in the United States: Assessment of opportunities and barriers." National Renewable Energy Laboratory report, Sept. 2010.

[4] J. Ribrant and L. Bertling, "Survey of failures in wind power systems with focus on Swedish wind power plants during 1997-2005," in *IEEE Power Engineering Society General Meeting*, 2007.

[5] A. M. Ragheb and M. Ragheb, *Wind Turbine Gearbox Technologies*, ch. 8, pp. 189–206. InTech, 2011.

[6] D. McMillan and G. Ault, "Specification of reliability benchmarks for offshore wind farms," in *European Safety and Reliability (ESREL) Conference*, 2008.

[7] A. Sannino, H. Breder, and E. Nielsen, "Reliability of collection grids for large offshore wind parks," in *International Conference on Probabilistic Methods Applied to Power Systems*, 2006.

[8] B. Backlund and S. Ebner, "The wind power converter for tomorrow is already here," in *EWEA*, 2011.

[9] R. Grinberg, S. Ebner, and O. Apeldoorn, "Reliability in medium voltage converters for wind turbines," in *EWEA*, 2011.

[10] E. Wiggelinkhuizen, T. Verbruggen, H. Braam, L. Rademakers, J. Xiang, and S. Watson, "Assessment of condition monitoring techniques for offshore wind farms," *Journal of Solar Energy Engineering*, vol. 130, pp. 031004.1–031004.9, 2008.

[11] M. Parker, "An evaluation of possible collection network architectures for offshore wind farms," in *Supergen*, 2011.

[12] P. Steimer and O. Apeldoorn, "Medium voltage power conversion technology for efficient windpark power collection grids," in *IEEE International Symposium on Power Electronics for Distributed Generation Systems*, 2010.

[13] O. Holmstrom, "Survey of reliability of large offshore wind farms, part 1: Reliability of state-of-the-art wind farms," tech. rep., Project Upwind, Aug. 2007.

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