Farhana Fayaz, et. al. International Journal of Engineering Research and Applications
www.ijera.com
ISSN: 2248-9622, Vol. 11, Issue 12, (Series-II) December 2021, pp. 32-40

RESEARCH ARTICLE OPEN ACCESS

Criticality Analysis of different topologies of Wind Turbine System

Farhana Fayaz[1], Abubakar Isa[2]
[1]Research Scholar, Electrical Engineering Department
National Institute of Technology Kurukshetra, India
[2]Research Assistant, Ruhr-Universität Bochum,Universitaetsstrasse 150
44801 Bochum, Germany

ABSTRACT
Wind Energy is among the fastest growing renewable energy sources. With an increase in the power generation from wind farm, the complexity and the size of the plant is increasing. Also, wind turbine system needs to be ultra reliable for the uninterrupted supply of electricity. For these systems to be ultra reliable, there is a need to have knowledge of the reliability of existing wind turbine system and its parts as well as the scope to improve the reliability. There is a significant impact of wind turbine failures on public health, economy, productivity and safety. It is therefore a challenging task for wind turbine manufacturers to achieve the desired reliability and safety during the design and operation stage. Hence there is a need to go for efficient design and manufacturing techniques. One of such techniques is the criticality assessment of wind turbine components/sub systems which ranks the components in order of criticality. In this paper reliability modeling and evaluation of different wind turbine configurations has been carried out. Different techniques that exist in literature for reliability modeling and evaluation have been reviewed. Major limitations of these methods have been pointed out and have been overcome in present paper. Also, criticality analysis of different wind turbine configurations has been done which will play an essentialtask in optimizing the operational and maintenance procedures for obtaining a better reliability and operational safety of wind turbines. To the best of our knowledge this is the first attempt to compare the criticality of various wind turbine topologies.

Keywords: Criticality Analysis, Reliability, Safety, Wind Turbine Configurations.

Date of Submission: 16-12-2021 Date of Acceptance: 31-12-2021

I. INTRODUCTION

There has been a considerablerise in the use of renewable energy sources from past two decades [1]. Among these energy sources, one of the fastest growing sources is the wind energy [2]. It can provide power free of pollution and it occupies a significant proportion in power grid. However, large utilization of wind energy creates some problems in terms of reliability and availability.

Also, one of the keyaspects in the planning and operation of wind energy is the reliability evaluation and optimization. The reliability evaluation and optimization of wind turbine system is expected to receive more attention in future, due to increase in generation from wind energy resources.

There exists literature on the reliability evaluation and design improvements of wind turbines [3-17]. The failure of wind turbine components affects the efficiency of windplant [18-21]. The large wind turbine system comprisesdifferent sub systems/components at different hierarchical levels and each sub system/component follows different failure patterns [22-23]. This results in increased system complexity, poor maintenance and reliability as well as difficulty in accessing faulty components. The failure rates and unreliability of the components of wind plant directly affects the operational and maintenance cost. It is therefore difficult to achieve a high reliability during the design and operational phase of the system. Although research has been done regarding reliability aspects of wind turbine system [24-27], yet there is limited literature on the cruciality assessment of wind turbine components regarding the failure rates/characteristics.

The most common tool for accessing the criticality of wind turbine system is effect analysis (FMEA) and failure mode. In FMEA, the criticality rank is calculated using a risk priority number (RPN) that is a function of severity, occurrence, and detection. However, the failures of different elements in a system also depend on the system structure. Thus, the drawback of FMEA is that it does not consider the structure of the system [28,29].

Component importance measures assign a criticality ranking for system components in order to improve reliability and maintenance. To put it another way, importance measures assess the contribution of specific system components to overall performance (e.g., reliability, availability, risk). The significance of component maintenance has been prioritized according to their ranks [30]. The cost of maintaining the components and the cost of designing the system may both be decreased by prioritizing system components using Importance measures [31]. Different component importance measures, such as Fussell-Vesely (FV) importance, Birnbaum importance, risk reduction, differential importance, structure important, and so on, have been proposed in the literature [30, 31-37]. [38] Proposed a Birnbaum-importance-based genetic algorithm for finding the near global optimum solution for a linear consecutive-k-out-of-n system. The authors of [39] provided an importance analysis of each component of a wind turbine system's electrical, control, and hydraulic subsystems.

II. WIND TURBINE STRUCTURE AND COMMON TOPOLOGIES OF WIND TURBINE SYSTEM

For the analysis of wind turbine'sreliability, it is essential to explore the available design configurations and elucidate the function of the most important sub systems including the components of the turbine system.

The turbine system consists of several sub-assemblies or components that work together for the efficient and reliable transformation of kinetic energy into electrical energy. Broadly the components of turbine system are categorized into three sub-assemblies as electrical, mechanical and control systems. Components such as the drive train, tower, nacelle, rotor blades, rotor hub, gear box, pitch drives, yaw drives, wind speed sensors, and mechanical brakes are included in the mechanical sub assembly [41]. The components in the electrical sub assembly include generator, power electronic converter, harmonic filters, etc. [42]. The components related to the control system are used for the electrical and mechanical energy conversion [43]-[45]. Tower, nacelle, blades and the hub are the visible parts in a large wind turbine system and rest components are found inside the system.

a) Wind Turbine Sub-assemblies

i. Mechanical Sub-assembly

The kinetic energy is converted into mechanical energy by using aerodynamically shaped rotor blades. The most common and efficient design in wind turbines is the three blade design [46], [47]. The blades are designed from glass fiber reinforced plastic and are light weight and sturdy. The blades are designed with advanced techniques for the protection against lightening and heating within the blades. The centered structure that links the blades to the shaft is a hub which is manufactured using cast iron. The nacelle, hub and tower act as a mechanical support for the blades. The efficiency of the wind energy conversion depends on the wind speed, density of air, angle of the blades, etc [48]. Sensors measure the velocity and direction of the wind. Based on the wind direction, the nacelle is oriented by the yaw for the extraction of maximum energy. Since the wind turbines run at lower torques and very low speeds, a multistage gear box is required. The law speed shaft and high-speed shaft is coupled by the gear box. Usually a 3-stage gear box is used in high-speed generators. If the generator speed can be matched with the wind turbine speed, the gear box can be eliminated. The wind turbine in that case is referred to as direct driven. The direct driven concept was introduced first in Germany in 1992 (Enercon Model). The drawbacks of the direct driven technology are higher weight and large diameter [49]. For the safety reasons, brakes are provided to stop the wind turbines on the occurrence of faults or during high winds. Both mechanical brakes and aerodynamic brakes are used in a wind turbine system.

ii. Electrical Sub-assembly

This sub-assembly consists of the components that deliver the electrical energy to the grid as well as control the power. Electrical generator transforms the mechanical energy into the electrical energy. The type of generator employed in a wind turbine plant varies. The commonly used generators for wind turbines include induction generator and synchronous generator [50]-[54]. Induction generators can be operated at high speeds and the synchronous generators operate at low, medium, and highspeeds. The output power from the generators is supplied to the grid either directly or by means of converters (power electronic) which control the power and frequency. Various topologies of power electronic converters have been derived for the turbine systems. The use of converters results in switching harmonics which are reduced using harmonic filters.

iii. Control Sub-assembly

Power output, wind speed, wind direction, voltages and currents in the generator and grid are surveyed and controlled around the reference value by use of the control unit. The main task of the control system is monitoring, control and automation so that the operation of the wind turbine plant is optimized. In case of high wind speed, the control system activates passive stall or pitch control systems to change the blade angle in turn to keep the turbine power output at the rated value. The sensors measure the temperature, wind speed, wind direction, vibrations etc. and are connected to the control system.

b) Common Topologies of Wind Turbine System

By connection of wind turbines in various manners and by the different combination of generators, a wide variety of wind turbine configurations can be developed. A number of wind turbine configurations have been achieved so far [55]-[60]. The commonly used wind turbine topologies are grouped into three categories based on speed variation as given below

i. Fixed Speed Configuration
ii. Semi variable speed configuration
iii. Full variable speed configuration

i. Fixed Speed Configuration

At different wind speeds, the rotor speed is varying around 1% of the synchronous speed and thus this configuration is termed as fixed-speed configuration. This concept is also known as "Danish concept" and is the oldest technology that has been evolved for the wind turbines. The induction generator is connected to the power grid by means of a step-up transformer [61]-[63]. With the aim of match the speed of the turbine and the generator, a gear box is employed. The system lacks power electronic converters, and the squirrel cage induction generator absorbs the reactive power from the grid which is then compensated by the capacitor[64], [65]. This topology is simple with consistent operation and has less initial cost. The demerits of this configuration are lower conversion efficiency and stress on the components due to faults. . The wind industry has commercialized this configuration, for example, Vestas, Micon, and Tacke [66].

ii. Semi- Variable Speed Configuration

Based on the speed of theincoming wind, the rotor speed varies within certain limits. Due to the variable speed, there is reduction in the wear-and-tear of bearings and gearbox, reduction in stress, reduction in maintenance and hence increase in the life cycle of the wind plant. The energy losses caused by the resistance of the rotor, the requirement for reactive power compensation, the limited speed range, and the low transformation efficiency are all disadvantages of this arrangement. Due to the combination of generator and power electronic converter, the semi-variable speed configuration has two design topologies as given below

a) First topology with Wound Rotor Induction Generator (WRIG) and partial rated convertor (10%)
b) Second topology with Doubly Fed Induction generator (DFIG) and partial rated converter (30%)

In first topology, the speed adjustment is in the range of ±10% and the speed deviation in the second topology is ±30% of the rated speed. DFIG based configuration is currently dominating technology in the wind industry with a share of 50% in the market [67], [68]. The reason for dominance is the increased efficiency by employing Maximum Power Point Tracking (MPPT), improved dynamic performance, variable speed range (±30%), sturdiness against the disturbances. The drawbacks of DFIG based configuration include increased maintenance due to slip rings and brushes, increase in cost and weight due to the use of gear box as well as the maintenance of the gear box. Some commercial manufacturers of semi-variable speed wind turbine configuration include Siemens, Vestas etc. [66].

iii. Full-Variable Speed Configuration

This configuration uses fully rated power electronic converters tocontrol the frequency and voltage levels as per the specifications of the network and hence enhances the performance. The generators which have been employed in this topology include wound rotor synchronous generator, permanent magnet synchronous generator and squirrel cage induction generator. The advantages of this type of configuration include smooth grid connection, operation at full speed range (0 to 100%) reactive power compensation by power electronic converters, higher conversion efficiency, robust because of the absence of gear box. The drawbacks of this topology are increase in size, more complexity and increase in cost as the power electronic converter should be rated at the level of generator capacity. In addition, losses in the power electronic converters reduce efficiency. The typical turbines of this configuration that have been developed commercially include Enercon, Vestas V-112, Multibrid, DeWind etc. [66]

1. Reliability of Wind turbine Configurations

a) Basics of Reliability

Reliability of a component is defined quantitatively as the probability of the system/component performing its function adequately under the given conditions for the specified period of time. It is the probability of a system to function without any failure in a specified period of time 't'.

$$\mathrm{R}(t) = \mathcal{P}(\mathcal{T} > t)$$

Where, $t =$ time
$\mathrm{R}(t) =$ Reliability at time t

$$\mathbb{Q}(t) = 1 - \mathrm{R}(t) = \mathcal{P}(\mathcal{T} < t)$$

$\mathbb{Q}(t) =$ Unreliability at time t

A system containsseveral components. The reliability of the whole system is determined by the reliability of each component and the system structure. A system's components can be connected in series, parallel, or a series parallel.

i. System with series connected components

If the components in a system are connected in series, then the system functions if and only if all the components are functional. If we consider a system, having 'm' components which are connected in series, then the reliability of the system '$\mathrm{R}(t)$' is expressed as

$$\mathrm{R}_{series\ sys}(t) = \prod_{k=1}^{m} r_k(t)$$

Where $r_k(t) =$ reliability of of kth component

ii. System with parallel connected components

In a parallel system, at least one component must work for the system to function properly. If we consider a system having 'm' components which are connected in parallel, then the reliability of the system is given as

$$\mathrm{R}_{parallel\ sys}(t) = 1 - \prod_{k=1}^{m} q_k(t)$$

Where$q_k(t) =$ unreliability of kth component

$$q_k(t) = 1 - r_k(t)$$

iii. Reliability as a function of failure rate

Failure rate is the frequency with which a component fails. It is also defined as the number of failures occurring per unit time (per houror per year). It is calculated as the ratio of total number of failures 'N(f)' in a given time to the time taken for 'n' components to undergo the test. It is denoted by 'λ'.

$$\lambda = \frac{N(f)}{\mathcal{T}}$$

Where $\lambda =$ Failure Rate
N(f) = Number of components failed in the test
$\mathcal{T} =$ Time taken to test the given components

The failure rate is a function of time and hence for a system, the failure rate changes during the life cycle of the plant. With the increase in λ, the system reliability decreases. Reliability of a system as a function of $\lambda$is given as

$\mathrm{R}(t) = \exp\left(-\int_0^t \lambda(t)dt\right)$

For constant λ, the $\mathbb{R}(t)$ is given as

$\mathbb{R}(t) = \exp\left(-\lambda(t)dt\right)$

b) Reliability Block Diagram (RBD)

The RBD is a functional diagram that connects the system's elements. The components of RBD can be connected in series, parallel, or mix of the two. A series of components in a system (series RBD structure) state that all the components must be in good working order for the system to work correctly. In a parallel configuration, at least one of the components must be operational for the system to work properly.

c) Fault Tree Analysis (FTA)

Fault tree analysis is a deductive method for the evaluation of safety in a system. In a fault tree, the failure effects on a system are represented graphically i.e., the logical relationships between the failure events are represented by logic gates. FTA finds its use mostly in safety-critical systems, where the failure of one or more components may result in the loss of human lives as well as loss of money.

2. Component Importance Measures

i. Birnbaum Importance measure

The partial derivative of the plant's reliability h(p(t)) with respect to the component's reliability p_k is the Birnbaum important measure p_k(t).

$$I^B(k \mid t) = \frac{\partial \mathrm{h(p(t))}}{\partial P_k(t)} \quad (1)$$

Fault tree notation may also be used to write Birnbaum measures.

$$I^B(k \mid t) = \frac{\partial \mathrm{Q_O}\ (t)}{\partial P_k(t)} \quad (2)$$

$$I^B(k \mid t) = h(1_k, p(t)) - h(0_k, p(t)) \quad (3)$$

When component 'k' moves from a condition of success to a state of failure, the Birnbaum importance measure shows a decrease in system reliability. The disadvantage of this measure is that it is unaffected by component reliability, therefore two components with different individual reliabilities may have the same value for the Birnbaum Importance measure.

ii. Improvement potential Importance measure

The improvement potential for aelement I at time t is defined as

$$I^{IP}(k \mid t) = h(1_k, p(t)) - h(p(t)) \quad (4)$$

$I^{IP}(k \mid t)$ is the difference between the system's reliability when a component 'k' has 100 percent reliability and the system's reliability when the component 'k' possesses actual reliability.

iii. Fussell Vesely importance measure

The possibility of failure of at least one minimum cut set including component k at time t, known that the system is in a failed state at time t, is Fussell-importance Vesely's measure, $I^{FV}(k|t)$.
$I^{FV}(k|t)$, the Fussell-Vesely importance measure, is defined as

$$I^{FV}(k|t) = \frac{\sum_{i=1}^{m} Q_i^k(t)}{Q_0(t)} \quad (5)$$

Where, $Q_i^k(t)$ = failure probability of minimal cut set I with component "k" at time t.

3. Ranking of Wind Turbine components in relationsto criticality

The wind turbine components of the most common topologies of wind turbine system have been ranked using Birnbaum Importance Measure, Improvement Potential and Fussel Vesely Importance measure. The topologies that are compared in terms of criticality include fixed speed configuration (Micon), Semi-variable speed configuration (Vestas), and Full-variable speed configuration (Enercon). The data for failure rates of these configurations have been taken from [66]. The importance measures have been applied to the components of wind turbine plant in all the three configurations and then the results are compared.

III. RESULTS

Figure 1 shows the criticality ranking of wind turbine system components of fixed speed configuration. Figure 2 shows the rankings of components in terms of criticality for Semi-variable speed configuration. The criticality ranking of the components in full-variable speed configuration of wind turbine is depicted in figure 3.

In all the three configurations electric system is found to be most critical. Since each of the configuration has some different components e.g., full rated power electronic converter is present only in full-variable speed configuration. Hence it is necessary to carry out the criticality analysis of each topology. The criticality of each component can be compared in each type of configuration. That means we can clearly evaluate how the criticality of a particular component varies from one topology to the other.

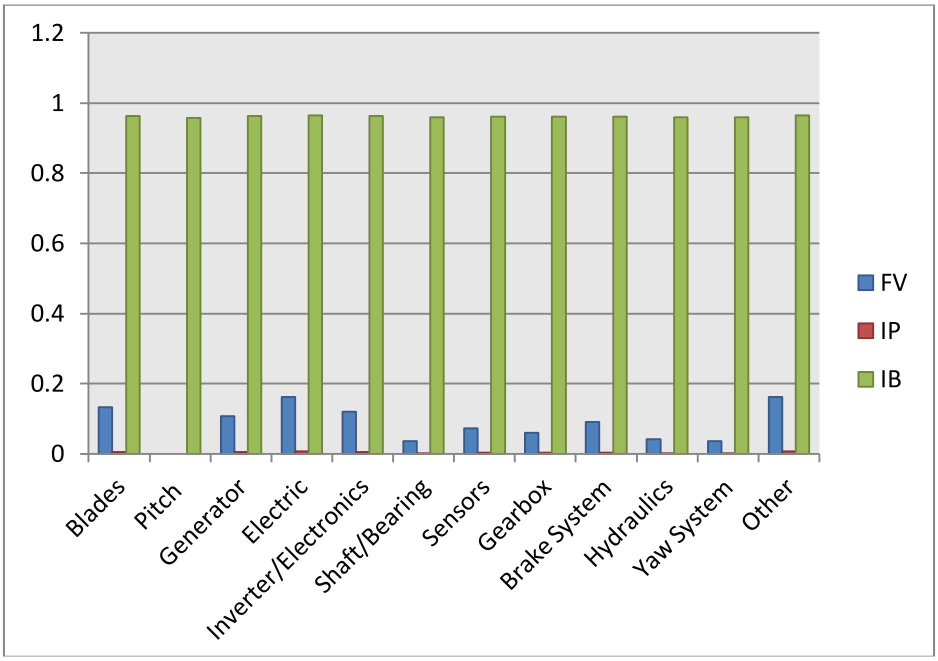

Figure 1: Criticality Ranking of Fixed Speed Configuration (Micon)

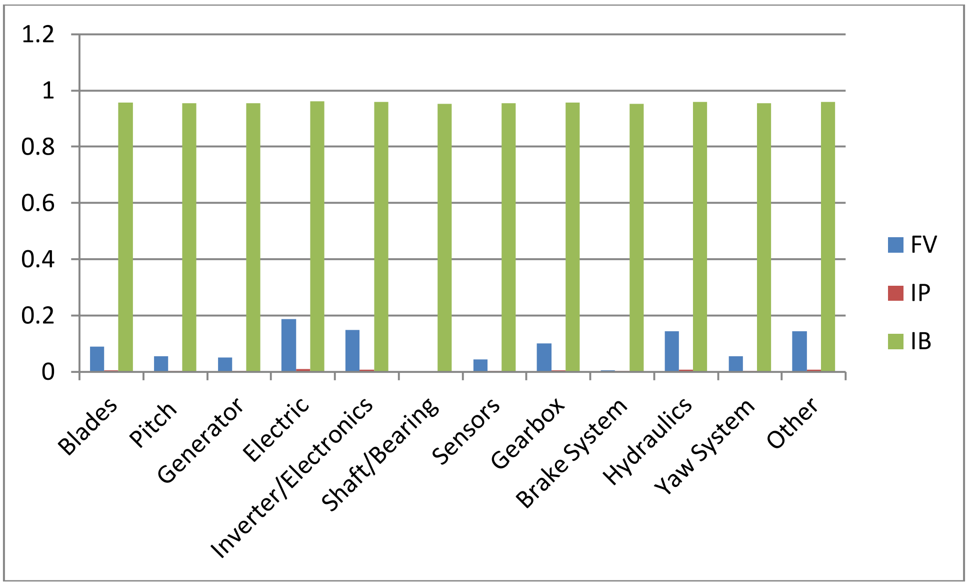

Figure 2: Criticality Ranking of Semi-variable Speed Configuration (Vestas)

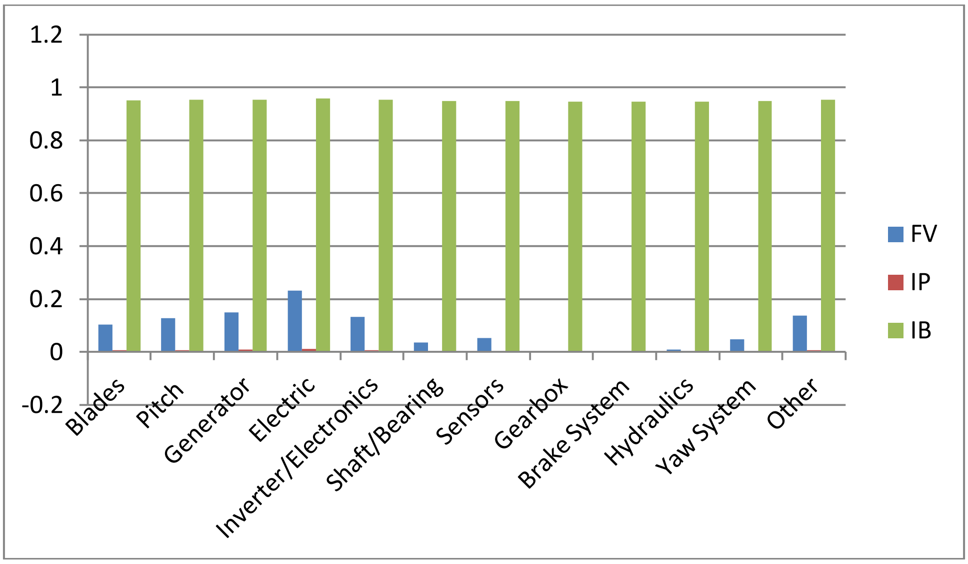

Figure 3: Criticality Ranking of Full Variable Speed Configuration (Enercon)

IV. CONCLUSION

Wind turbine technology is advancing greatly mostly in past forty years, and there are currently a number of horizontal axis machines on the market.The most critical design options were reviewed and compared, illustrating that each option has advantages and limitationswhich should be studied during different planning stage of a wind turbine. The reliability of the most significant topologies was examined using the LWK-SH database of wind turbine failures.Micon M1500, Enercon E-40, and Vestas V39 are three wind turbine models that each represent a different topology, based on the quantity of data given in terms of the number of monitored units and years of operation.Mid-power class machines had 2 to 5 failures per wind turbine per year, according to a review of more than 10 operating years of failure data for these onshore wind plants in Germany. The criticality assessment of the most common wind turbine topologies has been carried out. The importance measures used for the criticality analysis include Birnbaum importance measure, Fussel Vesely importance measure and Improvement Potential importance measure. Using failure rate data from the literature, all of the components in the three configurations are ranked in terms of criticality. Each configuration's most critical and least critical components have been identified. This type of analysis will play n vital role in the design phase of a wind turbine. The most critical component can be repaired or replaced with a highly reliable component in turn to develop the overall system reliability. Since each of the topology has its own structure and the components have different failures rates in different configurations. Hence the criticality analysis of each type of configuration is essential.

REFERENCES

[1]. R. Moeini, P. Tricoli, H. Hemida, C. Baniotopoulos, "Increasing the reliability of wind turbines using condition monitoring of semiconductor devices: a review", Proc. IET Renewable power generation conference, 2016.
[2]. N. Buaossa, M. Aldricy, K. Ragab, Z. Rajab, A. Tahir and A. Khalil, "Practical design and performance evaluation of micro-wind turbine in Libya," 2018 9th International Renewable Energy Congress (IREC), Hammamet, 2018, pp. 1-6..
[3]. Tavner PJ, Bussel GJW van, Spinato F. Machine and Converter Reliabilities in Wind Turbines. In: Proceedings of 3rd international conference on power electronics, machines and drives 2006 (PEMD 06); 2006: 12730.
[4]. Bussel GJW van, Zaaijer MB. Reliability, availability and maintenance aspects of large-scale offshore wind farms. In: Proceedings of the 2001 European wind energy conference, Copenhagen, Denmark.2011: 55760
[5]. Tavner PJ, Xiang J, Spinato F. Reliability analysis for wind turbines. Wind Energy. 2007; 10: 118.
[6]. Ribrant J. Reliability performance and maintenancea survey of failures in wind power systems. Master’s thesis. Stockholm: KTH School of Electrical Engineering. 2006.
[7]. Braam H, Rademakers LWMM. Models to analyse operation and maintenance aspects of offshore wind farms. ECN Report. 2004.
[8]. Mcmillan D, Ault GW. Towards quantification of condition monitoring benefit for wind turbine generators. In: Proceedings of European wind energy conference and exhibition, Milan. 2007.
[9]. Bin Lu, Yaoyu Li, Xin Wu, Yang Z. A review of recent advances in wind turbine condition monitoring and fault diagnosis. In: proceedings of IEEE power electronics and machines in wind applications,PEMWA. 2009: 17.
[10]. Windstats newsletter database. Denmark. Available from: www.windstats. com.
[11]. Ribrant J, Bertling LM. Survey of failures in wind power systems with focus on Swedish wind power plants during 19972005. IEEE transactions on Energy Conversion. 2007; 22: 16773.
[12]. Spinato F, Tavner PJ, Bussel GJW van, Koutoulakos E. Reliability of wind turbine subassemblies. Renewable Power Generation, IET. 2009; 3(4): 387401.
[13]. Tavner P, Gindele R, Faulstich S, Whittle M, Greenwood D, Hahn B. Study of effects of weather and location on wind turbine failure rates. In: Proceedings of the European wind energy conference EWEC; 2010
[14]. Rademakers LWMM, Braam H, Zaaijer MB, Bussel GJW van. Assessment and optimization of operation and maintenance of off shore wind turbines. ECN Windenergie. June 2003. Available from: http://www.ecn.nlł.
[15]. Tavner PJ, Edwards C, Brinkman A, Spinato F. Influence of wind speed on wind turbine reliability. Wind Engineering. 2006; 30(1): 5572
[16]. McMillan D, Ault GW. Condition monitoring benefit for onshore wind turbines: sensitivity to operational parameters. Renewable Power Generation, IET. 2008; 2(1): 6072.
[17]. Bussel GJW van, Zaaijer MB. Estimation of wind turbine reliability figures within the DOWEC project. Report Nr. 2003; 10048(4).
[18]. Nivedh, B.S. Major failures in the wind turbine components and the importance of periodic inspections. www.windinsider.com [Accessed 29 June 2017]
[19]. Gowdar, R.D. and Mallikarjune Gowda, M.C. 2016. Reasons for wind turbine generator failures: a multicriteria approach for sustainable power production. Renewables: Wind, Water, and Solar [DOI: 10.1186/ s40807–016–0029–1]
[20]. Reder, M.D., Gonzalez, N. and Melero, J.J. 2016. Wind turbine failures—tackling current problems in failure data analysis. Journal of Physics: Conference Series [DOI:10.1088/1742–6596/753/7/072027].
[21]. Alewine, K. and Chen, W. 2011. A review of electrical winding failures in wind turbine generators. IEEEElectrical Insulation Conference, 5–8 June, Annapolis, MD, USA.
[22]. Johnson, G.L. 2006. Wind energy systems. Kansas State University. Manhattan, USA.
[23]. Jain, P. 2011. Wind energy engineering, McGraw-Hill, Inc. United States.
[24]. Tavner, P. J., Xiang, J. and Spinato, F. 2007. Reliability analysis for wind turbines. Wind Energy 10 (1): 1–18.
[25]. Hahn, B., Durstwitz, M. and Rohrig, K. 2006. Reliability of wind turbines—Experiences of

15 years with 1500 WTs. German Wind Energy Report, ISET, Kassel.

[26]. Arabian-Hoseynabadi, H., Oraeea, H. and Tavner, P. J. 2010. Failure modes and effects analysis (FMEA) for wind turbines. Int J Electr Power Energy Syst., 32: 817–824.

[27]. Guo, H., Watson, S., Tavner, P. J. and Xiang, J. 2009. Reliability analysis for wind turbines with incomplete failure data collected from after the date of initial installation. Reliability Engineering and System Safety 94 (6): 1057–1063.

[28]. Loganathan, M.K and Gandhi, O.P. 2015. Reliability evaluation and analysis of CNC cam shaft grinding machine. Journal of Engineering, Design and Technology 13 (1): 37–73.

[29]. Loganathan, M.K., Minu Shikha Gandhi, and Gandhi, O. P. 2015. Functional cause analysis of complex manufacturing systems using structure. Proceedingsof the Institution of Mechanical Engineers, Part B:Journal of Engineering Manufacture 229(3): 533–545.

[30]. Z.W. Birnbaum, On the importance of different components in a multi-component system, Krishaniah, P.R. (Ed.), Multivariate Analysis, Vol. 11, New York: Academic Press, 1969.

[31]. X. Gao, J. Barabady, and T. Markeset, "Criticality analysis of a production facility using cost importance measures", International Journal of Systems Assurance Engineering and Management, vol. 1, pp. 17-23, 2010.

[32]. J.B. Fussell, "How to hand-calculate system reliability and safety characteristics", IEEE Transactions on Reliability, vol. R-24, pp. 169-174,1975.

[33]. M. van der Borst and H. Schoonakker, "An overview of PSA importance measures", Reliability Engineering & System Safety, vol. 72(3), pp. 241-245, 2001.

[34]. S. Epstein and A. Rauzy, "Can we trust PRA?", Reliability Engineering & System Safety, vol. 88, pp. 195-205, 2005.

[35]. W. Kuo and X. Zhu, "Relations and generalizations of importance measures in reliability", IEEE Transactions on Reliability, vol. 61, pp. 659-674, 2012.

[36]. W. Kuo and X. Zhu, "Some recent advances on importance measures in reliability", IEEE Transactions on Reliability, vol. 61, pp. 344-360, 2012.

[37]. W. Kuo and X. Zhu, Importance measures in reliability, risk and optimization: principles and applications, John Wiley & Sons: Chichester, UK, 2012.

[38]. X. Zhu, and W. Kuo, "Importance measures in reliability and mathematical programming", Annals of Operations Research, vol. 212, pp. 241-267, 2014.

[39]. Z. Cai, S. Si, S. Sun, and C. Li, "Optimization of linear consecutive-k-out-of-n system with a Birnbaum importance-based genetic algorithm", Reliability Engineering & System Safety, vol. 152, pp. 248-258, 2016.

[40]. S. Katsavounis, N. Patsianis, E.I. Konstantinidis and P.N. Botsaris, "Reliability Analysis on Crucial Subsystems of a Wind Turbine through FTA Approach", Proceedings of Maintenance Performance Measurement and Management (MPMM), Sep. 2014.

[41]. J. Manwell, J. McGowan, and A. Rogers, Wind Energy Explained: Theory, Design, andApplication, 2nd ed. Hoboken, NJ, USA: Wiley, 2009.

[42]. B. Wu, Y. Lang, N. Zargari, and S. Kouro, Power Conversion and Control of Wind Energy Systems, 1st ed. Hoboken, NJ, USA: Wiley-IEEE, Jul. 2011, ser. IEEE Press Series on Power Engineering.

[43]. T. Orlowska-Kowalska, F. Blaabjerg, and J. Rodrguez, Advanced and Intelligent Control in Power Electronics and Drives. New York, NJ, USA: Springer, 2014.

[44]. L. Y. Pao and K. Johnson, ''Control of wind turbines,'' IEEE Control Syst. Mag., vol. 31, no. 2, pp. 44–62, Apr. 2011.

[45]. V. Yaramasu, ''Predictive control of multilevel converters for Megawatt wind energy conversion systems,'' Ph.D. dissertation, Ryerson Univ., Toronto, ON, Canada, 2014.

[46]. P. S. Veers et al., ''Trends in the design, manufacture and evaluation of wind turbine blades,'' Wind Energy, vol. 6, no. 3, pp. 245–259, 2003.

[47]. S. Eriksson, H. Bernhoff, and M. Leijon, ''Evaluation of different turbine concepts for wind power,'' J. Renew. Sustain. Energy Rev., vol. 12, no. 5, pp. 1419–1434, 2008.

[48]. S. Heier, Grid Integration of Wind Energy Conversion Systems, 2nd ed. Hoboken, NJ, USA: Wiley, 2006.

[49]. Y. Duan and R. Harley, ''Present and future trends in wind turbine generator designs,'' in Proc. IEEE Symp. Power Electron. Mach. Wind Appl. (PEMWA), Lincoln, NE, USA, Jun. 2009, pp. 1–6.

[50]. L. H. Hansen et al., Conceptual Survey of Generators and Power Electronics for Wind Turbines. Roskilde, Denmark: DenmarkRiso

National Lab., Dec. 2001, Riso-R-1205(EN). [Online]. Available: http://orbit.dtu.dk.

[51]. L. Greedy, Review of Electric Drive-Train Topologies. Bristol, U.K.: Garrad Hassan and Partners, May 2007, 11593/BR/01. [Online]. Available: http://www.upwind.eu.

[52]. T.-F. Chan and L.-L. Lai, ‘‘Permanent-magnet machines for distributed power generation: A review,’’ in Proc. IEEE Power Energy Soc. (PES) Gen. Meet., Tampa, FL, USA, Jun. 2007, pp. 1–6.

[53]. H. Polinder et al., ‘‘Trends in wind turbine generator systems,’’ IEEE J. Emerg. Sel. Topics Power Electron., vol. 1, no. 3, pp. 174–185, Sep. 2013.

[54]. E. Camm et al., ‘‘Characteristics of wind turbine generators for wind power plants,’’ in Proc. IEEE Power Energy Soc. (PES) Gen. Meet., Calgary, AB, Canada, Jul. 2009, pp. 1–5.

[55]. F. Blaabjerg, Z. Chen, and S. Kjaer, ‘‘Power electronics as efficient interface in dispersed power generation systems,’’ IEEE Trans. Power Electron., vol. 19, no. 5, pp. 1184–1194, Sep. 2004.

[56]. European Commision, 2013 JRC Wind Status Report: Technology, Market and Economic Aspects of Wind Energy in Europe, Aug. 2014. [Online]. Available: http:// setis.ec.europa.eu/

[57]. A. D. Hansen, F. Iov, F. Blaabjerg, and L. H. Hansen, ‘‘Review of contemporary wind turbine concepts and their market penetration,’’ Wind Eng., vol. 28, no. 3, pp. 247–263, 2004.

[58]. R. L. Iglesias, R. L. Arantegui, and M. A. Alonso, ‘‘Power electronics evolution in wind turbines VA market-based analysis,’’ J. Renew. Sustain. Energy Rev., vol. 15, no. 9, pp. 4982–4993, 2011.

[59]. E. Camm et al., ‘‘Characteristics of wind turbine generators for wind power plants,’’ in Proc. IEEE Power Energy Soc. (PES) Gen. Meet., Calgary, AB, Canada, Jul. 2009, pp. 1–5.

[60]. Z. Zhu and J. Hu, ‘‘Electrical machines and power-electronic systems for high-power wind energy generation applications: Part IV Market penetration, current technology and advanced machine systems,’’ COMPEL: Int. J. Computat. Math. Elect. Electron. Eng., vol. 32, no. 1, pp. 7–33, 2013.

[61]. H. Li and Z. Chen, ‘‘Overview of different wind generator systems and their comparisons,’’ IET Renew. Power Gener., vol. 2, no. 2, pp. 123–138, Jun. 2008

[62]. H. Polinder et al., ‘‘Trends in wind turbine generator systems,’’ IEEE J. Emerg. Sel. Topics Power Electron., vol. 1, no. 3, pp. 174–185, Sep. 2013.

[63]. D. Trudnowski, A. Gentile, J. Khan, and E. Petritz, ‘‘Fixed-speed wind-generator and wind park modeling for transient stability studies,’’ IEEE Trans. Power Syst., vol. 19, no. 4, pp. 1911–1917, Nov. 2004.

[64]. B. Wu, Y. Lang, N. Zargari, and S. Kouro, Power Conversion and Control of Wind Energy Systems, 1st ed. Hoboken, NJ, USA: Wiley-IEEE, Jul. 2011, ser. IEEE Press Series on Power Engineering.

[65]. J. Dixon, L. Moran, J. Rodrı´guez, and R. Domke, ‘‘Reactive power compensation technologies: State-of-the-art review,’’ Proc. IEEE, vol. 93, no. 12, pp. 2144–2164, Dec. 2005.

[66]. E. Koutoulakos, “Wind turbine reliability characteristic and offshore availability assessment,” Master’ thesis, TU Deift.2008.

[67]. R. Cardenas, R. Pena, S. Alepuz, and G. Asher, ‘‘Overview of control systems for the operation of DFIGs in wind energy applications,’’ IEEE Trans. Ind. Electron., vol. 60, no. 7, pp. 2776–2798, Jul. 2013.

[68]. M. Liserre, R. Cardenas, M. Molinas, and J. Rodrı´guez, ‘‘Overview of multi-MW wind turbines and wind parks,’’ IEEE Trans. Ind. Electron., vol. 58, no. 4, pp. 1081–1095, Apr. 2011.