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# Horizontal axis wind turbine review with emphasis on tower structural stability, failure issues, and remedial measures in practice in wind power industries

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## ABSTRACT

Advancements in materialistic life styles and increasing awareness about adverse climatic changes and its negative effects on human life have been the driving force of finding new and clean sources of energy. Wind power technology has become technologically mature and commercially acceptable on a global scale. Though fossil fuels have been the major sources of energy in most countries, renewable energy (particularly wind energy) is now booming worldwide. To cope with this wind energy technology, various related aspects have to be understood by the scientific, engineering, utility, and contracting communities. This study is a review effort towards the understanding of the (i) wind turbine blade and tower structural stability issues, and (ii) turbine blade and tower failures and remedial measures.

## 1. INTRODUCTION

Exponentially growing population and even more rapidly increasing power demands have resulted in adverse effects on the environment due to the burning of fossil fuels to cope up with the power demands. However, the realization of unhealthy effects due to change in climatic conditions on the life of people has received efforts from all walks of life to overcome the adverse conditions of the climate and to meet the power demands at the same. In this context, renewable and clean sources of energy are being developed and encouraged to be included into the energy mix on local and national levels around the globe. These sustainable sources of energy include wind, solar photovoltaic, solar thermal, geothermal, biomass, and ocean to name some. Among these clean sources, wind power receiving more attention has commercially developed and accepted by the industries and people. The wind power plants or farms can be realized in a minimum possible time after the wind resource assessment exercise.

The cost of wind power generation has reduced to 4–7 US cents per kilowatt-hour.

Generally speaking, as a rule of thumb, each MW of wind power installed capacity costs around one million USD. The wind farms require a minimum maintenance cost and attention of the skilled manpower. It is also evident from the fact that the cumulative global wind power installed capacity reached 539.581 GW with a new addition of 52.573 GW in year 2017 (Global Wind Report 2017). The annual growth of wind power installed capacity is shown in Fig. 1. Since 2014, more than 50 GW new capacities have been added every year (Fig. 1). The global cumulative annual wind power capacity increases almost linearly as shown in Fig. 2. In year 2016, the wind power installed capacity was 488 GW while it increased to 540 GW in 2017, an increase of almost 11%. However in 2016, the wind power equipped capacity was increased by 13%. At present, there are more than 90 countries contributing towards wind power capacity build-up including 9 countries with more than 10 GW and 29 more than 1 GW of installed capacities globally. The power installed capacity can be represented by a polynomial equation fitted using a least square method as:

$$P = 1.961x^2 - 6.467x + 27.655 \qquad (x \geq 1),$$
$$\approx 1.96(x^2 - 3.3x + 14), \qquad (1)$$

where $P$ is the power in GW and $x$ is the number of years starting with 1 at year 2000. When the $x$ is represented by the actual year $Y$, Eq. (1) can be reduced to,

$$P \approx 1.96[(Y - 2000)^2 - 1.3Y + 2611] \qquad (Y \geq 2000) \qquad (2)$$

Modern wind turbine blades are mostly built-up of fiber-reinforced composites manufactured through molding process. The common blade designing technique comprises of independent productions of the suction and pressure side shells (Eder and Bitsche 2015). In the concluding stage, the two halves are adhesively connected of which the most important adhesive joint appears at the trailing edge that refers to the downstream edge of a blade wherein the flow around the airfoil rejoins and exits the blade (Fig. 3).

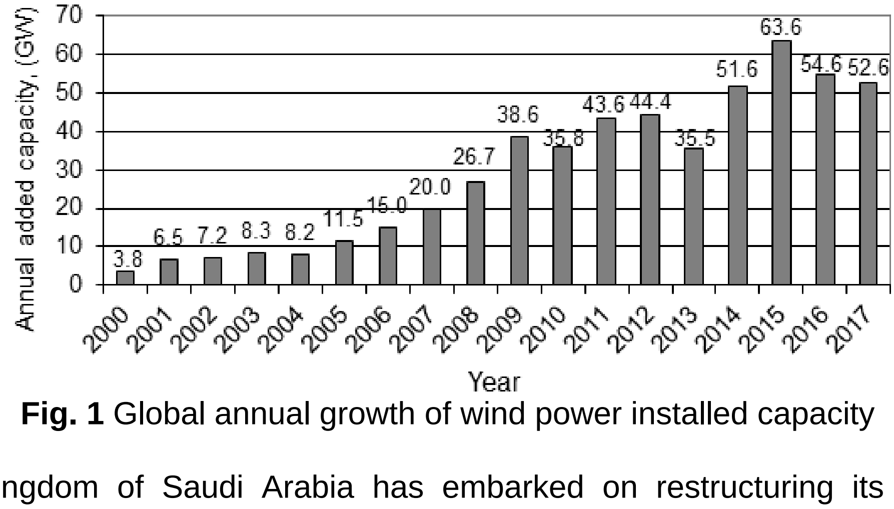

**Fig. 1** Global annual growth of wind power installed capacity

The Kingdom of Saudi Arabia has embarked on restructuring its energy mix portfolio by supplementing the existing capacity through wind power and solar photovoltaic. Hence, as a consequence of it, large wind turbines of capacities ranging from 2 to 3.5 MW and even more will be installed in different operating areas of the

Kingdom. Such large wind turbines are expected to have rotor diameters ranging from 80 to 120 meters and hub heights of 80 to 120 meters. In the last 10 years, a great deal of research initiatives have been under taken on wind power related topics such as (i) understanding of the wind speed behavior and its prediction using artificial neural network and other techniques (Shoaib et al. 2017, Islam et al. 2017, Mohandes and Rehman 2016, Mohandes and Rehman 2014, and Mohandes et al. 2011), (ii) wind turbine selection and wind farm lay out design using fuzzy logic and multi-criteria methodologies (Rehman and Khan 2017, Rehman et al. 2016, Rehman and Khan 2016), (iii) wind power resource assessment, wind characteristics and feasibility (Zheng et al. 2017, Alam et al. 2014, Baseer et el. 2017, Himri et al. 2016, Bagiorgas et al. 2013, Rehman et al. 2016, Baseer et al. 2016, Rehman et al. 2015, Baseer et al. 2015, Bassyouni et al. 2015, Rehman 2014, Rehman et al. 2013, Rehman 2013, Rehman 2012, Rehman et al. 2012, Rehman et al. 2012, Bagiorgas et al. 2012, McVicar et al. 2011, Bagiorgas et al. 2011, and Alam et al. 2011).

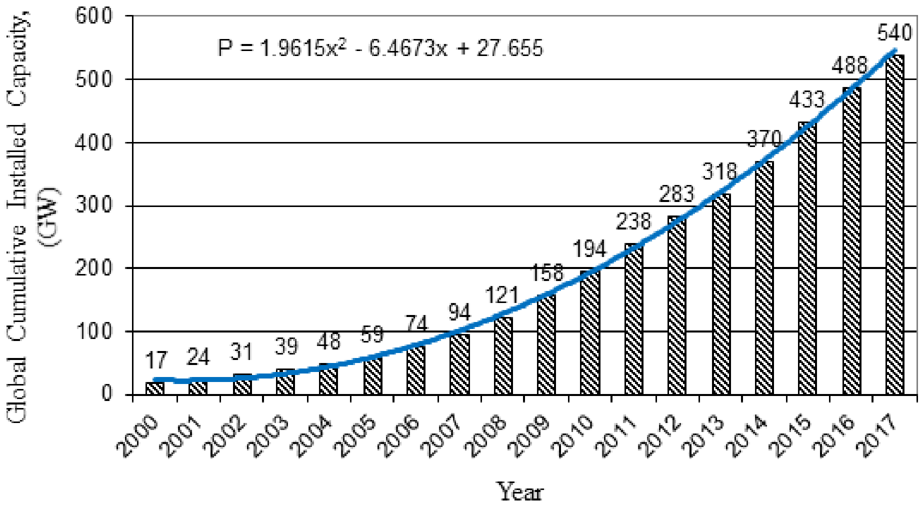


**Fig. 2** Global cumulative annual growth of wind power installed capacity.

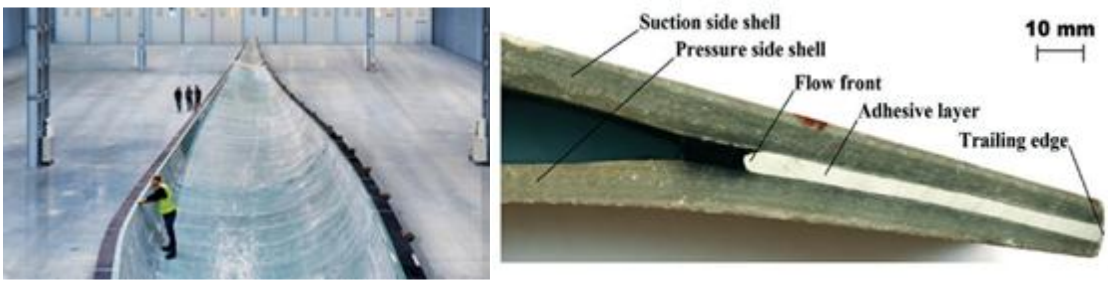


**Fig. 3** Adhesive trailing edge joint of wind turbine blade as manufactured (Eder and Bitsche 2015)

The present work emphasizes the need of studying the structural stability of wind turbine blades and towers, related failure issues, and prevailing remedial measures adopted internationally.

## 2. WIND TURBINE BLADE AND TOWER STRUCTURAL STABILITY ISSUES

As stated earlier, the cumulative wind power capacity has reached around 540 GW by the end of 2017. This simply tells that there are around 350,000 large operational wind turbines around the world in the present time. The wind turbines are always located at sites where effective wind resources are available. Usually, these are the remote open locations away from the cities and inhibited areas. To keep turbines in operation continuously and safely and being profitable is, therefore, a challenging task and has to be addressed well. Furthermore, the operation and maintenance tasks of remotely located wind turbines become sophisticated due to the following wind resources dependent issues (Yang et al. 2014):

Sites: Wind turbines have been installed largely in remote onshore areas and offshore locations with larger wind resources.

Diversity: These days, wind turbines are manufactured based on different technologies such as geared-drive, direct-drive, variable geared, synchronous generators, permanent magnet generators, induction generators, and gearless wind turbines. Of these concepts, the wind turbine market is driven by the geared-drive technology based wind turbines.

Sizes: The capacity and size of wind turbines increases rapidly to harvest more energy from wind. Figure 4 shows existing and expected growth in turbine size and production for land-based and offshore turbines. The growth in size is larger for the offshore turbines because the offshore turbines produce more power per square meter than the land-based turbines. Different manufacturers have focused on different technologies to adopt the capacity and size, for example, Enercon has developed 7 MW rated power wind turbine while Repower 3.4 MW, GE 4.0 MW, Gamesa 4.5 MW, XEMC Darwind 5 MW, and so on.

Control: Modern wind turbines are fitted with more intelligent control systems to work over a large range of wind speed, such as active pitch-regulated and variable-speed systems. Initially, wind turbines used to work on passive stall-regulated load control in a narrow wind speed range. The newly developed individual blade pitch control enables the turbines to generate more power with smaller blades and towers (Leithead et al. 2009; Leithead and Chatzopoulos 2010). Present day smart blade control techniques are being developed with built-in wind measuring sensors to allow the blades to follow the wind conditions (Dvorak 2012).

Economics: An increase in the wind turbine size directly reduces the cost of wind energy generation per kWh. However, in the case of offshore deployment it is not true, rather the energy generation cost increases due to installation and power cable laying complexities.

It has been observed and reported that extreme winds are mainly responsible for the damage of the structural integrity of the blades and towers. The extreme wind scenarios are usually observed in the coastal and open areas. Fortunately, turbines are usually located in the coastal areas due to high available wind resources. To validate the wind shear estimations utilized in simulating the loads for the design of wind turbine, Dimitrov et al. (2015) used wind speed data measured at two stations at heights between 60 and 200 m for several years. They proposed a model for flat terrain, capable of reducing the ambiguity associated with fatigue load estimations. The model was used to evaluate the wind shear over different sections of the wind turbine with wind conditions provided in IEC 61400-1 ed. 3 standard. The results showed that, under moderate turbulence conditions, the effects of Woehler exponent and wind shear was prominent on the blade flap loads but not on tower fatigue loads (Figs. 5a, c). An increase in the wind shear component leads to an increase in the fatigue damage load on the blades (Fig. 5b).

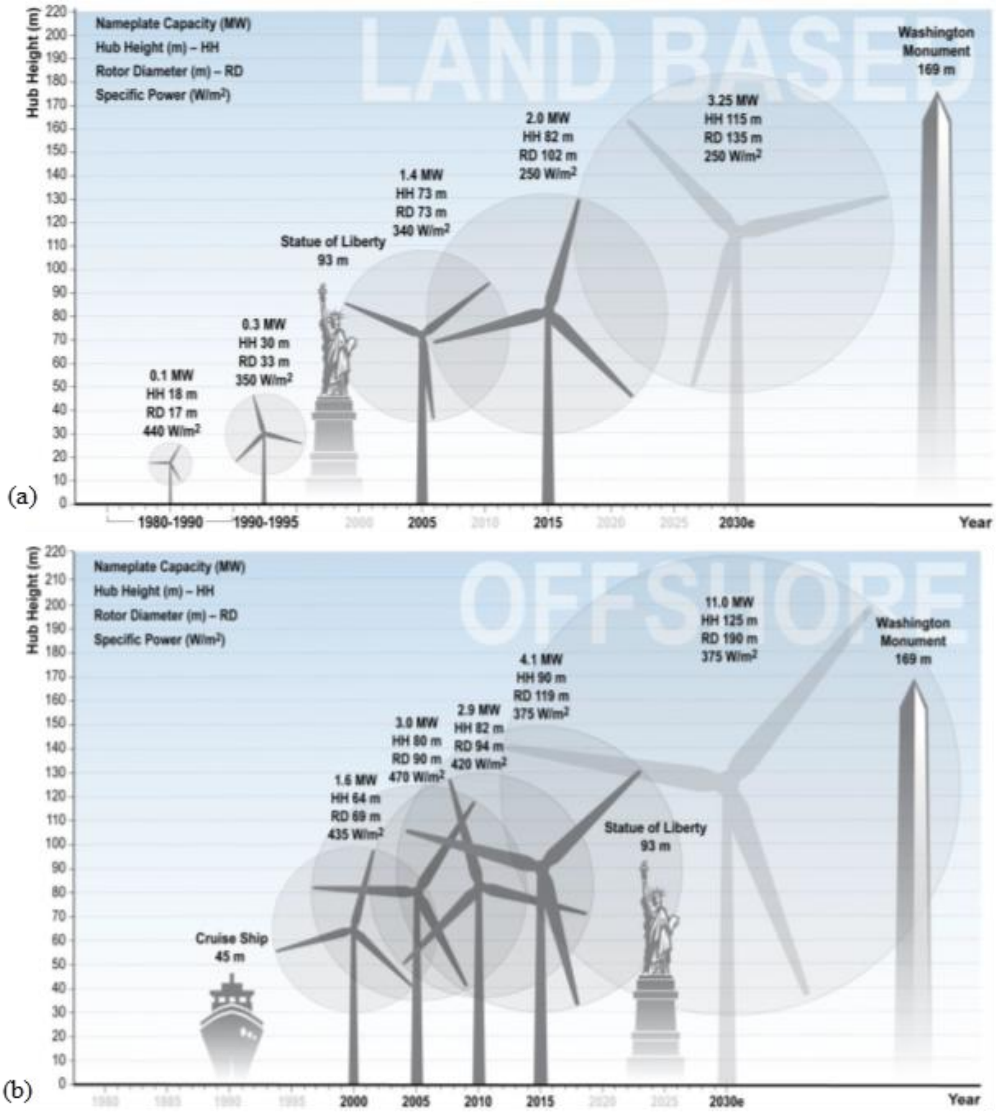


**Fig. 4** (a) Existing and expected growth in turbine size and production for (a) land-based turbines in North America, and (b) offshore turbines around the world Wiser et al. (2016).

Traditionally, the towers are tubular, made of structural steel. These towers are manufactured in large sections in factory environment and transported to the installation site. Today's modern wind turbines have grown up in sizes, and the hub height often reaches somewhere between 80 to 120 m (Alam et al. 2011; Rehman et al. 2013). With such large hub heights, it has become must to design and develop concrete or some other material towers to facilitate improved dynamic properties

(Kenna and Basu 2015). The transportation of long steel towers is a challenge in itself which can be addressed by using concrete or other new material towers. Kenna and Basu (2015) proposed a finite element model for the design of concrete as a continuum of four-noded, two-dimensional Reisser–Mindlin shell element. The authors studied the effect of changing the magnitude of pre-stress and related time dependence and the impact compressive strength of concrete on the stiffness of the tower.

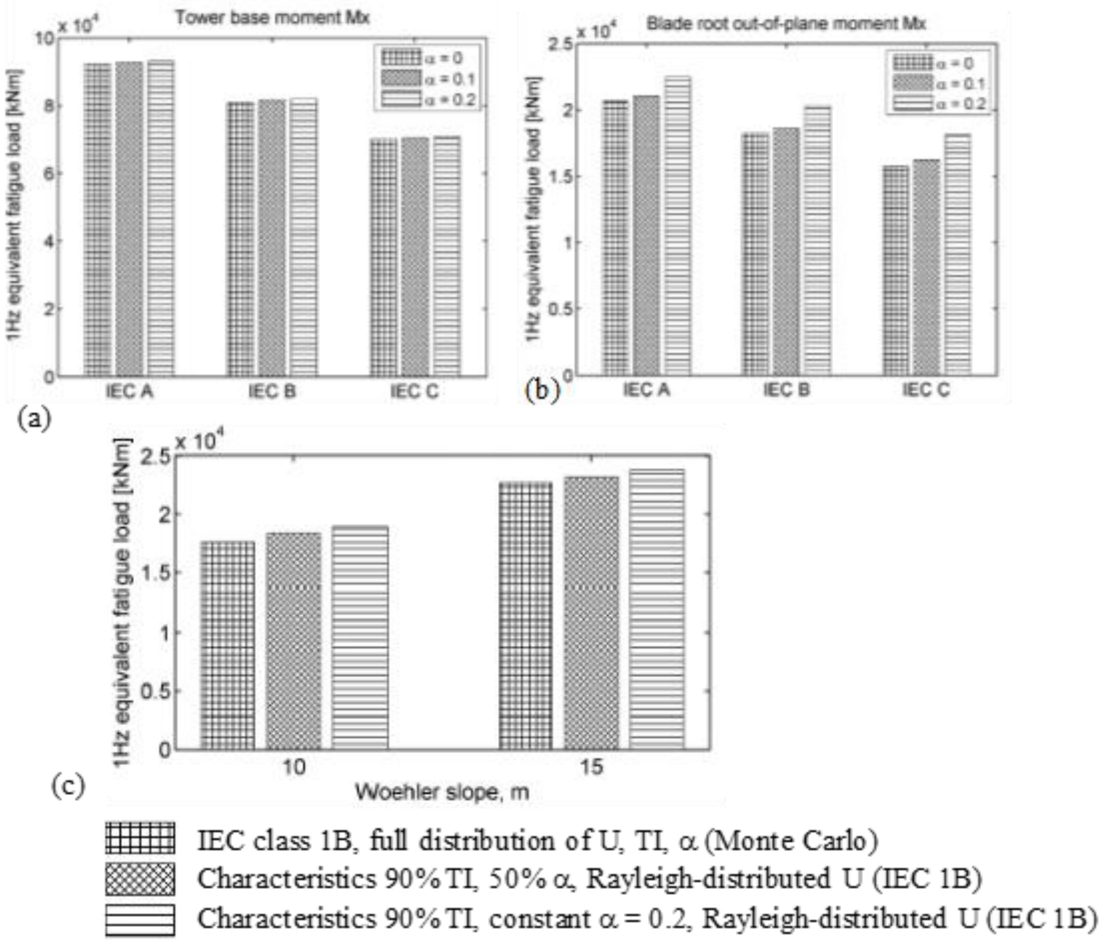


**Fig. 5** Influence of wind shear exponent $\alpha$ on equivalent fatigue moment at (a) tower base and (b) blade root. (c) Effect of Woehler exponent m on flapwise fatigue load at blade root (Dimitrov et al. 201).

## 3. BLADE AND TOWER FAILURES AND REMEDIAL MEASURES

With passage of time, failures of wind turbine blade and tower have been reduced to a greater extent. It is the consequence of more reliable wind turbine blade manufacturing that has been possible due to continued efforts made in resolving and addressing the usual failure causes. However, with the ever-growing industrial volume of wind turbine installations, new problems and challenges emerge. Of these failures, some belong to aging of the turbines, reaching specified fatigue life limits; some are due to material defects and shortcomings in the manufacturing process; and lastly, some are relatively newer inadequate modes related to the bigger rotor size and equally increasing hub heights. It is a fact that as the number of turbines grows on the ground or ocean, the accidents are also expected to increase. Figure 6 depicts numbers of wind turbine accidents occurred globally in different years, from 2000 till 2017 (Weblink-03 2018). It is evident from these numbers that when the wind turbines were less in place, the number of accidents was also less (e.g. years 2000-2005), increasing according to the growing number of wind turbine installations. Between 2000 and 2005, the average number of accidents was 57 per year while during 2006-2010 this number reached 118 accidents per year. Between 2013 and 2017, the average number of accidents reached to around 167 per year.

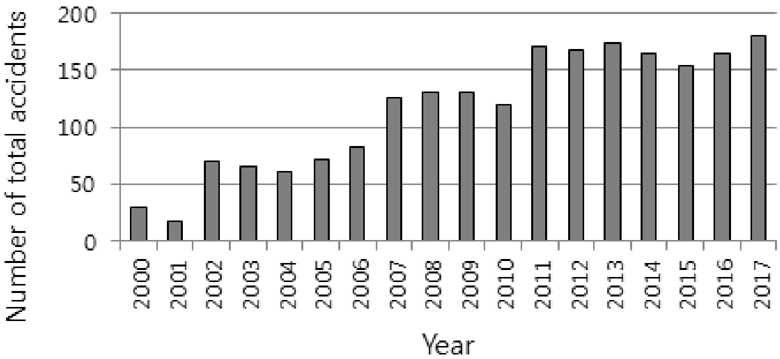


**Fig. 6** Annual statistics of global wind-turbine accidents (Weblink-03 2018).

The numbers of blade and structural failures on the global level are shown in Fig. 7. It is evident from the figure that the number of structural failures is much less than the blade failures. The maximum number of wind turbine blade failures (35) occurred in 2013 while that of structural failures (16) in 2009. This means that more technological development is required in the area of wind-blade interaction, blade manufacturing techniques, and developing new materials to reduce the failures (Alam et al. 2010; Qin et al. 2017; Kim et al. 2018). Blade failures may cause the entire blades or pieces of blade being separated from the turbine. A piece of blades due to the centrifugal and Coriolis forces can travel upto 1.6 km, depending on the rotor size and speed. Some scraps of blades went through the roofs and walls of nearby buildings in an incidence in Germany, which suggests that wind turbines should be installed at least 2 km away from residential buildings. Some of the peculiar wind turbine tower and blade failure cases are shown in Fig. 8 (Weblink-04 2018 and Weblink-05 2018). Furthermore, the weather conditions do play an important role in blade and tower failures.

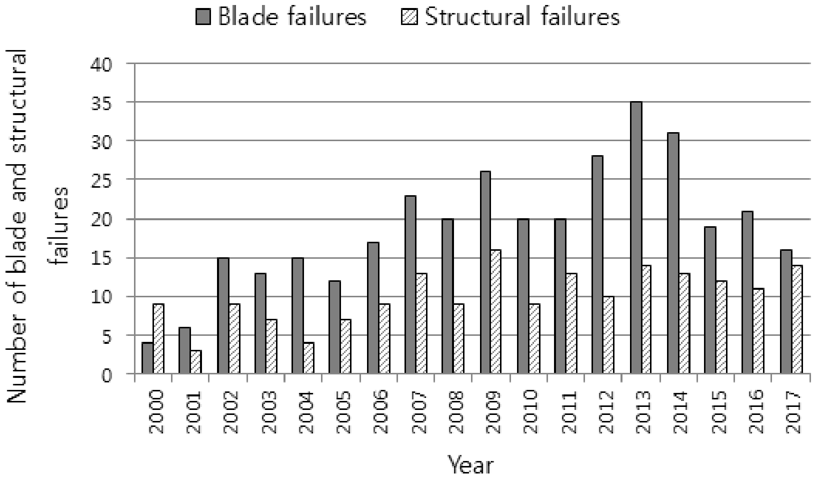


**Fig. 7** Comparison of annual statistics between blade and tower failures (Weblink-03 2018).

Kress et al. (2015) in an experimental study measured and compared yaw stability of three different downwind rotors with corresponding upwind rotors by using a wind turbine model allowing upwind or downwind operation. The investigation showed yaw stability for downwind rotor configuration at full-scale Reynolds numbers while upwind turbines were either not stable and/or had reduced stability. Downwind configurations with 0°, 5° and 10° cone resulted in higher shaft power and rotor thrust than the corresponding upwind configurations. However, for zero yaw and 5° and 10° cone angles, the downwind configurations resulted in 5% additional power and have 3% higher thrust compared to upwind configurations. The study stated that the coned downwind configurations give easier yaw control and more power. Abdallah et al. (2015) proposed a rational stochastic model to quantify the uncertainty in airfoil static lift and drag coefficients based on field and wind tunnel data, aero-servo-elastic calculations, and engineering judgment. The results showed that the ambiguity in the static airfoil data has a significant impact on the prediction of extreme load effects and structural reliability. This depends on the component, operating conditions, and the correlations of aerodynamic variables along the span of the blades.

(a)  (b)

**Fig. 8** (a) Wind turbine tower and blade failure example (Weblink-04 2018), (b) Wind turbine blade failure example (Weblink-05 2018).

Lin et al. (2016) reviewed the failures of wind turbine parts; like blades, generators, gearboxes, frequency converters, pitch and yaw systems, braking systems and sub-synchronous machines based on the three primary configurations and failure statistics analysis data of wind turbines in China. Four primary reasons were revealed by the study for failures; (i) lack of core technologies, (ii) compromised material quality, (iii) climatic conditions and design standards, and (vi) lack of certification and knowledge of exterior factors. The study proposed a management system for the design, manufacturing, and maintenance of wind turbines aiming at improved reliability. Pascu et al. (2016) investigated the tower damping control in situations when support structure parameters vary from nominal design values and turbine's natural frequency proposed an adaptive tower damping control loop utilizing linear parameter-varying control synthesis. The study demonstrated the fatigue load reduction performance relative initial tower damping control approach for horizontal axis wind turbine.

## 4. BLADE AND TOWER FAILURES

Chou et al. (2013) conducted a wind turbine blade failure analysis by examining the cause of damages, specifically the delamination and cracking in blades. They also critically studied the literature to point out the usual reasons for turbine blade failures. The structural mechanics of blades studied with behavioral models to understand the mechanisms of the damage. Chen and Xu (2016) studied the structural failure phenomenon of turbines due to very high winds (Fig. 9) such as super typhoon Usagi in 2013 using post mortem analysis (PMA). Usagi caused failures of eight wind turbines inclusive of towers, rotor blades, generators, gear boxes, etc. Including cracked blades on the intact towers, the total number of the blade failures was 35 i.e. 46.7% of the total number of blades. The tower wall thickness was varied with the tower height, and the steel shells were joined with butt welding. Though failures of the towers were in buckling mode, the estimated elastic buckling strength, considering the stress concentration due to the butt joint, proved that the towers were strong enough to sustain steady loads by the wind (Fig. 9). It was, therefore, inferred that the tower collapse was due to the elastic response to the wind. The study suggested modification of the current IEC design standard and provided some directions in order to minimize the risk of failures in wind turbines under severe wind conditions.

The post mortem analysis has emerged as a useful approach in software engineering to obtain and analyse elements of a completed project in order to be successful or unsuccessful (Collier et al. 1996). This process involves finding out the root causes of problems, proposing process improvements that can help in mitigating the risks of future projects (Dingsoyr 2005; Bjornson et al. 2009). The PMA has been used successfully in analysing the failures of polyvinylidene fluoride pipes (Gacougnolle et al. 2006), power transformers by temperature distribution on surfaces (Carcedo et al. 2014), refractory linings (Queiroga et al. 2013), and compression of cast Al-Si alloys (Asghar and Requena 2014).

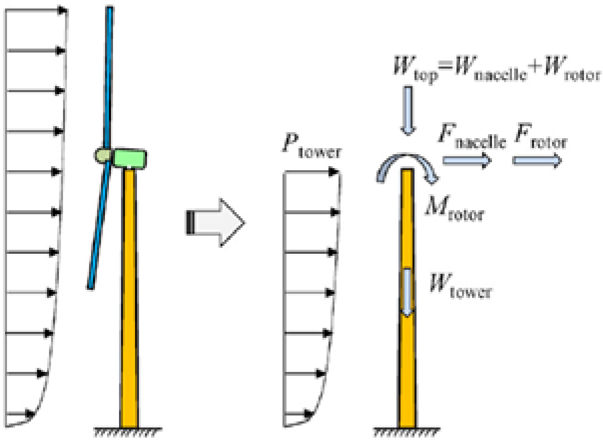


**Fig. 9** External loads subjected on the turbine tower (Chen and Xu 2016)

Ishihara et al. (2005) investigated the failure of two turbine towers due to typhoon Maemi in Japan in 2003 and realized that the maximum bending moment was larger than their maximum bending moment. Chou and Tu (2011) and Chou et al. (2013) analyzed the reasons for tower collapse and blade damage of a wind turbine during typhoon Jangmi in Taiwan in 2008. The study found that lesser strength and poor quality of bolts were the reasons for the collapse of towers. On the other hand, in case of blade damages, poor blade material strength, wind frequency, resonance effects, and human errors (during turbine installation) were identified as the main causes. Zhang et al. (2013) conducted a series of experiments to find out the cause of shaft failure (Fig. 10) including the chemical composition and mechanical properties and showed that there were no noticeable differences in the main shaft's material and mechanical properties compared to the Standard, EN10083-3:2006. The analysis revealed that stress concentration on the shaft surface coupled with high-stress concentration resulted from the change of the inner diameter of the main shaft were the main reasons for fracture. Additionally, the theoretical stresses at the end of the shaft demonstrated that cracks can appear due to the impact of the load.

Many studies have provided useful data to evaluate failure behaviour and the main causes of large wind turbine blades through full-scale structural tests. In this regard, Jensen et al. (2006, 2011, 2012) conducted experimental investigations of a 34-m long wind turbine blade and its load-carrying spar girder to failure. It was learned that the Brazier effect induced large deformation in the spar cap and the blade was caused by delamination buckling. In another experimental study, Overgaard et al. (2010) and Overgaard and Lund (2010) tested a 25-m long blade to failure and found that the ultimate strength of the blade was caused due to the instability phenomena in the form of delamination and buckling. Yang et al. (2014) studied the structural collapse of a 40-m long blade and realized that the debonding of aerodynamic shells from adhesive joints was the root cause for the blade failure. Chou et al. (2013) investigated a typhoon-damaged composite blade of 39.5 m in length and demonstrated that the blade failed at a wind-speed of 53.4 m/s due to delamination and cracking, although it was supposed to resist forces up to a wind speed of 80 m/s. Chen et al. (2014) presented the preliminary findings of a large composite blade (52.3 m) failure analysis (Fig. 11). Static loads were applied to simulate extreme load conditions experienced by the blade. After failure, it was found that the blade exhibited multiple failure modes. Delamination of unidirectional laminates in the spar cap was found to be the primary cause of failure. Chen et al. (2014) revisited the structural collapse of a 52.3 m composite blade with a new approach to examine the chain of events captured in the video record of the blade collapse and provided direct phenomenological evidence of how the blade collapsed in its ultimate limit state. Lately, Chen (2018) carried out a forensic investigation of the fracture of 2 rotor blades taking into account interactive aspects associated with operational loads, materials, manufacturing processes, and structural design and recommended procedures to improve the structural integrity of the blades.

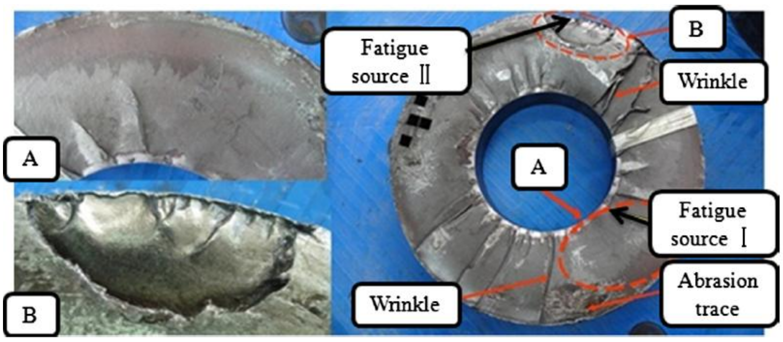


**Fig. 10** Macro-photograph of the fracture surface of the shaft (Zhang et al. 2013).

**Fig. 11** Wind turbine blades under flapwise bending before failure (Chen et al. 2014).

The inspection of faults detected in blades of 300 kW rated power turbines revealed that the failures were due to fatigue mechanism (Marin et al. 2009). The failure causes (e.g. superficial cracks, geometric concentrator, and abrupt change of thickness) were studied and verified by simplified evaluation procedure of fatigue life of the “Germanischer Lloyd” (GL) standard. Lacalle et al. (2011) analyzed the cracking cause in a wind turbine tower and observed cracks in the welded joint between the lower ring of the towers and the flange (Fig. 12) joining the towers with their foundations. To analyze the stress in the welded joints and fatigue analysis in accordance to the Fatigue Module of the FITNET FFS Procedure, a finite element simulation was conducted, reporting that inadequate design of the joint with high-stress concentrations and insufficient resistant section on the flange is the main cause of failure.

**Fig. 12** Corrosion presences in welded joint on the inner side of the tower (Lacalle et al. 2011).

Karthikeyan et al. (2015) reviewed cited blade profiles and aerofoil geometry optimization techniques to increase power coefficient in small wind turbines (Reynolds number < $5\times10^5$). Chehouri et al. (2015) presented a review of published techniques and strategies used for performance optimization of turbines through objective functions, design constraints, tools, models, and algorithms. Yang et al. (2016) presented a comprehensive overview of non-destructive testing (NDT) techniques for turbine blade inspection (Fig. 13) based on a concise literature survey. The review was based on studies focused on damages occurring during manufacturing and services and development of optical, sonic and ultrasonic, visual, thermal and radiographic nondestructive testing, and electromagnetic techniques. Wang et al. (2016) provided aero-elastic modelling, reviewed models for aerodynamic, analyzed structural and cross-sectional properties, and outlined the current implementations in the field of wind turbine blades.

Economic production of wind energy can be achieved by operating the wind turbines at/or near optimum efficiency during partial load operations, assuring reliability by fatigue load reduction, and regulating the power to rated value during rated wind availability. Njiri and Söffker (2016) reviewed control strategies, commonly used in wind turbines during low and high wind speed regimes focusing on multi-objective control schemes.

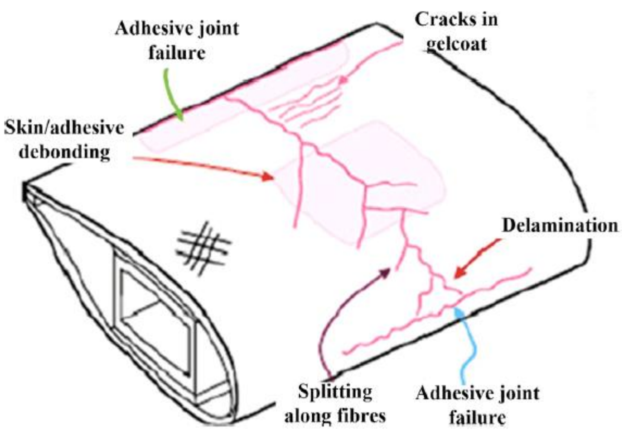


**Fig. 13** Types of damages that may be sustained by a wind turbine blade (Yang et al. 2016).

## 5. CONCLUSIONS

The present work aims at understanding various aspect of wind power technology for smooth implementation and adoption in the country. The study reviewed the existing understanding of the local expertise on the wind power subject and also focused on wind turbine blade and tower structural stability issues, blade and tower failures and remedial measures, weather and seismic effects on turbine blade and tower failures, gear box failures, and turbine blade and tower failure analysis tools. Some of the highlights of the present study are as follows.

- The existing domestic expertise included the wind power rehouse assessment using historical data and data collected using 40 to 100 meter tall wind masts, wind farm design and optimization, wind-diesel and wind-photovoltaic-diesel hybrid power systems design and optimization with and without energy storage, wind turbine selection using multi-criteria approach, prediction of wind speed with time and vertical extrapolation using artificial neural networks and fuzzy logic techniques, and wind speed estimation in spatial domain using machine learning techniques to name some.
- The reported failure histories showed that extreme winds are largely responsible for the damage of the structural integrity of the blades and towers. The average number of failure incidents increases with turbine density. Among the incidents, the number of blade failures is much higher than the tower failures. This is because Woehler exponent and wind shear have pronounced effect on the blade flap loads but not much on tower fatigue loads. An increased shear component results in an increased fatigue load on the blades. Researchers thus need to pay more attention to wind-blade interaction, manufacturing techniques, and developing new blade materials to reduce the failures.
- The turbine size increases rapidly day-by-day, the increase is however larger for the offshore turbines than for the land-based turbines because the offshore turbines produce more power per square meter than the land-based turbines. As such, an increase in blade extension is required, where the extension of a blade is done by bonding technology or by metal bolt connection. The bonded technology to extend blade size is simpler and adds less weight to the rotor, but increases the chance of fatigue damage. The failure of tower occurs largely in buckling mode due to the unsteady load generated by elastic response of the tower to the wind. To reduce wind turbine failure risk under extreme wind conditions (typhoon and hurricane), a modification of the current IEC design standard is thus suggested, incorporating the load due to the elastic response of the tower to the wind. The welded joint between the lower ring and the flange connecting the towers to the foundations, deteriorates rapidly particularly in the inner side of the shell, which should be paid attention when the tower base is designed. Gearbox failure causes longer downtimes and hence needs more attention of the engineering community to design more robust gearbox and develop lighter materials for its manufacturing. Fretting wear and fatigue source generation are the two main causes of gear box failures and must be addressed. Symmetrically arranged turbines may have a greater risk of failing all turbines simultaneously under extreme seismic event. It is thus required to conduct

experimental and theoretical modeling of turbine arrangement and to consider the nonlinear dynamic response of tower in the time domain.

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## REFERENCES

Abdallah, I., Natarajan, A., and Sørensen, J., (2015). “Impact of uncertainty in airfoil characteristics on wind turbine extreme loads”, Renewable Energy**, 75**, 283-300.

Alam, M.M., Rehman, S., Meyer, J.P., and Al-Hadhrami, L.M., (2011). “Review of 600-kW to 2500-kW sized wind turbines and optimization of hub height for maximum wind energy yield realization”, Renewable and Sustainable Energy Reviews, **15**, 3839-3849.

Alam, M. M., Zhou, Y., Yang, H. X., Guo, H. and Mi, J., (2010). “The ultra-low Reynolds number airfoil wake”, Experiments in Fluids, **48**, 81-103.

Alam, M.M., Rehman S., Meyer J., and Al-Hadhrami L. M., (2014). Extraction of the inherent nature of wind using wavelets, Energy for Sustainable Development **22**, 34-47.

Asghar, Z., and Requena, G., (2014). “Three dimensional post-mortem study of damage after compression of cast Al-Si alloys”, Mater. Sci. Eng. A **591**, 136–143.

Bagiorgas H.S., Mihalakakou G., Rehman S., and Al-Hadhrami L.M. (2013). Wind Power Potential Assessment for Three Buoys Data Collection Stations in Ionian Sea Using Weibull Distribution Function, International Journal of Green Energy, **13(7),** 703-714. DOI: 10.1080/15435075.2014.896258.

Bagiorgas H.S., Mihalakakou G., Rehman S., and Al-Hadhrami L.M., (2012). Offshore Wind Speed and Wind Power Characteristics for Ten Locations in Aegean and Ionian Seas, Journal of Earth System Science, v. 121(4), 975-987.

Bagiorgas H.S., Mihalakakou G., Rehman S., Al-Hadhrami L.M., (2012) Wind Power Potential Assessment for Seven Buoys Data Collection Stations in Aegean Sea Using Weibull Distribution Function, Journal of Renewable and Sustainable Energy, v. 4(1), February 2012, pp. 013119-013134.

Bagiorgas H.S., Mihalakakou G., Rehman S. and Al-Hadhrami L.M. (2011), Weibull parameters estimation using four different methods and most energy carrying wind speed analysis, International Journal of Green Energy, Vol. 8(5), pp. 529 – 554.

Baseer M. A., Meyer J.P., Rehman S., Alam Md. M., (2017). Wind power characteristics of seven data collection sites in Jubail, Saudi Arabia using Weibull parameters. Renewable Energy, **102**, 35-49. http://dx.doi.org/10.1016/j.renene.2016.10.040

Baseer M.A., Meyer J.P., Rehman S., Alam M.M., Al-Hadhrami L.M., and Lashin A., (2016). Performance Evaluation of Cup-anemometers and Wind Speed Characteristics Analysis. Renewable Energy, 86(2), pp. 733-744.

Bassyouni M., Saud A. G., Javaid U., Awais M., Rehman S., Abdel-Hamid S. M. S., Abdel-Aziz M. H., Abouel-Kasem A., and Shafeek H. (2015). Assessment and analysis of Wind Power Resource using Weibull Parameters, Energy Exploration & Exploitation 33(1), 105 - 122.

Bjornson, F.O., Wang, A.I., and Arisholm, E., (2009). “Improving the effectiveness of root cause analysis in post mortem analysis: a controlled experiment”, Inf. Softw. Technol. **51**, 150–161.

Bossanyi, E. (2003). GH Bladed Theory Manual. Garrad Hassan & Partners Ltd.: Bristol, 2003.

Carcedo, J., Fernandes I., Ortiz A., Carrascal I.A., Delgado F., Ortiz F., and Arroyo A., (2014). “Post-mortem estimation of temperature distribution on a power transformer: physicochemical and mechanical approaches”, Appl. Therm. Eng. **70**, 935–943.

Chehouri, A., Younes, R., Ilinca, A., and Perron, J., (2015). “Review of performance optimization techniques applied to wind turbines”, Applied Energy, **142**, 361-388.

Chen, X., Zhao, W., Zhao, X.L., and Xu, J.Z., (2014). “Preliminary failure investigation of a 52.3 m glass/epoxy composite wind turbine blade”, Engineering Failure Analysis, **44**, 345-350.

Chen X. 2018 Fracture of wind turbine blades in operation—Part I: A comprehensive forensic investigation. *Wind Energy*1-18. DOI: 10.1002/we.2212

Chen, X., and Xu, J.Z. (2016). “Structural failure analysis of wind turbines impacted by super typhoon Usagi”, Engineering Failure Analysis, **60**, 391-404.

Chou, J.S., and Tu, W.T., (2011). “Failure analysis and risk management of a collapsed large wind turbine tower”, Eng. Fail. Anal. **18**, 295–313.

Chou, J.S., Chiu, C.K., Huang, I.K., and Chi, K.N. (2013). “Failure analysis of wind turbine blade under critical wind loads”, Engineering Failure Analysis 27, 99-118.

Collier, B., DeMarco, T., and Fearey, P., (1996). “A defined process for project postmortem review”, IEEE Software **13(4)**, 65–72.

Dingsoyr, T., (2005). “Postmortem reviews: purpose and approaches in software engineering”, Inf. Softw. Technol. **47**, 293–303.

Gacougnolle, J.L., Castagnet, S., and Werth, M., (2006). “Post-mortem analysis of failure in polyvinylidene fluoride pipes tested under constant pressure in the slow crack growth regime”, Eng. Fail. Anal. **13**, 96–109.

Dimitrov, N., Natarajan, A., and Kelly, M. (2015). Model of wind shear conditional on turbulence and its impact on wind turbine loads, Wind Energy, **18**, 1917-1931.

Dvorak, P. (2012). “Can intelligent blades sense the wind and adapt”? Windpower Engineering & Development 2010. Available: http://www.windpowerengineering.com/ (Accessed March **27**, 2018).

Eder, M.A. and Bitsche R.D. (2015). “Fracture analysis of adhesive joints in wind turbine blades”, Wind Energy, **18**, 1007–1022.

Global Wind Report 2017 – Annual market update (GWEC - 2017), http://gwec.net/wp-content/uploads/vip/GWEC_PRstats2017_EN-003_FINAL.pdf (Accessed on 3rd March 2018).

Himri Y., Rehman S., Himri S., Mohammadi K., Sahin B., and Malik A. S. (2016). Investigation of Wind Resources in Timimoun, Algeria. Wind Engineering **40(3),** 250-260. DOI: 10.1177/0309524X16645483

Ishihara, T., Yamaguchi, A., Takahara, K., Mekaru, T., and Matsuura, S., (2005). "An analysis of damaged wind turbines by typhoon Maemi in 2003", The Sixth Asia-Pacific Conference on Wind Engineering (APCWE-VI), Seoul, Korea, September 12-14.

Islam Md. S., Mohandes M., and Rehman S., (2017). Vertical Extrapolation of Wind Speed Using Artificial Neural Network Hybrid System, Neural Computing and Applications, **28(8),** 2351-2361. DOI: 10.1007/s00521-016-2373-x

Jensen, F.M., Falzon, B.G., Ankerson, J., and Stang, H., (2006). "Structural testing and numerical simulation of a 34 m composite wind turbine blade", Compos Struct **76**, 52–61.

Jensen, F.M., Puri, A.S., Dear, J.P., Branner, K., and Morris, A., (2011). "Investigating the impact of non-linear geometrical effects on wind turbine blades – part 1: current status of design and test methods and future challenges in design optimization", Wind Energy **14**, 239–254.

Jensen, F.M., Weaver, P.M., Cecchini, L.S., Stang, H., and Nielsen, R.F., (2012). "The Brazier effect in wind turbine blades and its influence on design", Wind Energy **15**, 319–333.

Karthikeyan, N., Kalidasa, M.K., Arun, K.S., and Rajakumar, S., (2015). "Review of aerodynamic developments on small horizontal axis wind turbine blade", Renewable and Sustainable Energy Reviews, **42**, 801-822.

Kenna, A., and Basu, B. (2015). "A finite element model for pre-stressed or post-tensioned concrete wind turbine towers", Wind Energy, 18(9), 1593-1610.

Kim, S., Alam, M.M., and Maiti, D.K., (2018). "Wake and suppression of flow-induced vibration of a circular cylinder", Ocean Engineering, **151**, 298-307.

Kim, K.S., Yoo, J.S., Yi, Y.M., and Kim, C.G., (2006). "Failure mode and strength of uni-directional composite single lap bonded joints with different bonding methods", Compos. Struct. **72 (4)**, 477– 485.

Kress C., Chokani, N., and Abhari, R., (2015). "Downwind wind turbine yaw stability and performance", Renewable Energy, **83** , 1157-1165.

Lacalle**,** R., Cicero**,** S., Álvarez**,** J.A., Cicero**,** R., Madrazo**,** V., (2011). "On the analysis of the causes of cracking in a wind tower", Engineering Failure Analysis, **18(7),** 1698-1710**.**

Leithead, W., Neilson, V., and Dominguez, S. (2009). "Alleviation of unbalanced rotor loads by single blade controllers", Proceedings of European Wind Energy Conference (EWEC), Marseilles, France, March 16–19.

Leithead, W., and Chatzopoulos, A. (2010). "Reducing tower fatigue loads by a co-ordinated control of the Supergen 2MW exemplar wind turbine", Torque 2010: The Science of Making Torque from Wind, Proceedings of 3rd European Academy of Wind Energy (EAWE) Conference, Heraklion, Greece, June 28–30, 2010; 667–674.

Lin Y., Tu L., Liu H., and Li W., (2016). "Fault analysis of wind turbines in China", Renewable and Sustainable Energy Reviews, **55**, 482-490**.**

Marín, J.C., Barroso, A., París, F., Cañas, J., (2009). "Study of fatigue damage in wind turbine blades", Engineering Failure Analysis, **16(2)**, 656-668.

McVicar, T.R., Roderick, M.L., Donohue, R.J., Li, L.T., Van Niel, T.G., Thomas, A., Grieser, J., Jhajharia, D., Himri, Y., Mahowald, N.M., Mescherskaya, A.V., Kruger, A.C., Rehman, S., and Dinpashoh, Y. (2012) Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implication for evaporation. Journal of Hydrology, **417 – 417**, 182 – 205.

Mohandes M., and Rehman S., (2016). Convertible Wind Energy Based on Predicted Wind Speed at Hub-Height, Energy Sources Part A: Recovery, Utilization, and Environmental Effects **38(1),** 140-148.

Mohandes M., and Rehman S., (2014). Short Term Wind Speed Estimation in Saudi Arabia, Journal of Wind Engineering & Industrial Aerodynamics, **128**, 37-53.

Mohandes M., Rehman S., Rahman S.M., (2011), Estimation of wind speed profile using Adaptive Neuro-fuzzy Inference System (ANFIS), Applied Energy, **88**, 4024 – 4032.

Njiri, J.G., and Söffker, D., (2016). “State-of-the-art in wind turbine control: Trends and challenges”, Renewable and Sustainable Energy Reviews, **60**, 377-393.

Overgaard, L.C.T., Lund, E., and Thomsen, O.T., (2010). “Structural collapse of a wind turbine blade – part A: static test and equivalent single layered models”, Composite: Part A **41**, 257–270.

Overgaard, L.C.T., and Lund, E., (2010). “Structural collapse of a wind turbine blade – part B: progressive interlaminar failure models”, Composite: Part A **41**, 271–283.

Pascu, V., Kanev, S., and van Wingerden J-W., (2016), “Adaptive tower damping control for offshore wind turbines”, Wind Energy, **20(5)**, 765-796.

Qin, B., Alam, M.M. and Zhou, Y., (2017). “Two tandem cylinders of different diameters in crossflow: flow-induced vibration”, Journal of Fluid Mechanics, **829**, 621-658.

Queiroga, J.A., Campos, K.S., Silva, G.F.B.L., Souza, D.F., Nunes, E.H.M., Vasconcelos, W.L., (2013). Post mortem study of refractory lining used in FCC units, Eng. Fail. Anal. **34**, 290–299.

Rehman S., and Khan S.A., (2017). Multi-criteria Wind Turbine Selection using Weighted Sum Approach, International Journal of Advanced Computer Science and Applications, **8(6),** 128-132.

Rehman, S., Al-Hadhrami, L.M., Alam, M.M., and Meyer, J.P., (2013). “Empirical correlation between hub height and local wind shear exponent for different sizes of wind turbines”, Sustainable Energy Technologies and Assessments, **4**, 45-51.

Rehman S., Ali S.S., and Khan S.A., (2016). Wind farm layout design using cuckoo search algorithm. Applied Artificial Intelligence – An International Journal, **30(10),** 899-922. http://dx.doi.org/10.1080/08839514.2017.1279043

Rehman S., and Khan S., (2016). Fuzzy logic based multi-criteria wind turbine selection strategy – A case study of Qassim, Saudi Arabia, Energies, **9(11)**, Article No. 872. doi:10.3390/en9110872

Rehman S., Baseer M. A., Meyer J. P., Alam Md. M., L. Alhems M., Lashin A., and Al Arifi N., (2016). Suitability of utilizing small horizontal axis wind turbines for off grid loads in Eastern Region of Saudi Arabia, Energy Exploration and Exploitation, **34(3),** 449-467.

Rehman, S., Alam M. M., Alhems L. M., Lashin, A., and Alarefe, N., (2015). Performance Evaluation of Vertical Axis Wind Turbine for Small off grid loads in North-Eastern Region of Saudi Arabia. Wulfenia Journal **22(9),** 146 – 165.

Rehman S., (2014). Tower distortion and scatter factors of co-located wind speed sensors and turbulence intensity behavior, Renewable & Sustainable Energy Reviews **34**, 20–29.

Rehman, S., Al-Hadhrami, L. M., Alam Md. M., and Meyer J. P. (2013). Empirical Correlation between Hub Height and Local Wind Shear Exponent for Different Sizes of Wind Turbines, Sustainable Energy Technologies and Assessments **4**, 45-51. **DOI:** 10.1016/j.seta.2013.09.003

Rehman S., Alam, M. M., Meyer J. P., and Al-Hadhrami L. M., (2012), Wind Speed Characteristics and Resource Assessment using Weibull Parameters, International Journal of Green Energy, **9**, 800-814, DOI: 10.1080/15435075.2011.641700

Shoaib M., Siddiqui I., Rehman S., Rehman Saifur., and Khan S. (2017) Wind Speed Distribution Analysis using Maximum Entropy Principle and Weibull Distribution Function. Environmental Progress & Sustainable Energy, **36(5),** 1480-1489. doi/10.1002/ep.12589/epdf

Wang, L., Liu, X., and Kolios, A., (2016). "State of the art in the aeroelasticity of wind turbine blades: Aeroelastic modelling", Renewable and Sustainable Energy Reviews, **64**, 195-210.

Weblink-01 (2018). Horizontal axis wind turbine components explained: https://www.energy.gov/eere/wind/inside-wind-turbine-0 [Accessed on 17/05/2018].

Weblink-03 (2018). Global summary of the wind turbine accidents on annual basis. http://www.caithnesswindfarms.co.uk/AccidentStatistics.htm [Accessed on 28/03/2018].

Weblink-04 (2018). https://mothersagainstturbines.com/2016/04/07/2016-wind-turbine-accident-report/comment-page-1/ [Accessed on 28/03/2018]

Weblink-05 (2018). https://www.google.com.sa/search?q=wind+turbine+accidents&safe=active&dcr=0&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwid56Tbio_aAhWBERQKHar1AfcQsAQISA&biw=1920&bih=965#imgrc=1ZV-ywTuf_XRRM: [Accessed on 28/03/2018]

Yang, J.S., Peng, C.Y., Xiao, J.Y., Zeng, J.C., Xing, S.L., Jin, J.T., et al. (2013). "Structural investigation of composite wind turbine blade considering structural collapse in fullscale static tests", Compos Struct **97**, 15–29.

Yang, R., He, Y., and Zhang, H., (2016). "Progress and trends in nondestructive testing and evaluation for wind turbine composite blade", Renewable and Sustainable Energy Reviews, **60**, 1225-1250.

Yang, W., Tavner, P.J., Crabtree, C.J., Feng, Y., and Qiu, Y. (2014). "Wind turbine condition monitoring: technical and commercial challenges", Wind Energy **17**, 673–693.

Zhang, Z., Yin, Z., Han, T., and Tan, A.C.C., (2013). "Fracture analysis of wind turbine main shaft", Engineering Failure Analysis, **34**, 129-139.

Zheng Q., Rehman S., Alam Md. M., Alhems L.M., (2017). Wavelet and power spectrum based extraction of inherent properties of measured long-term wind speed data series. Journal of Earth System Science **126(3),** Article No. 36, 1-16, DOI 10.1007/s12040-017-0816-0.