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.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support provided by the Deanship of Scientific Research (DSR) at King Fahd University of Petroleum & Minerals (KFUPM) for funding this work through Grant number IN151026

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.