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FAULT DIAGNOSTIC METHODS FOR WIND TURBINE: A REVIEW

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ABSTRACT

Wind energy is one of the important renewable energy resources because of its reliability due to the maturity of the technology, relative cost competitiveness, good infrastructure which is obtained without any constraint. These wind energies are converted into electrical energy with the help of wind turbine to produce power. To harvest more electrical yield, the wind turbine must be bigger. Due to its large structure, periodic failures are inevitable. Maintenance of such large structure can be cumbersome. The wind turbines must be checked every now and then to enhance security, to minimize down time, to recurrence of sudden breakdowns with related to enormous maintenance and logistic expenses and to give a maximum potential output power generation. Structural health condition monitoring (SHCM) and fault diagnosis methods (FDM) are used to evaluate the damage which has occurred in wind turbine. This review gives comprehensive information on FDM and SHCM of a wind turbine.

Keyword: structural health condition monitoring, fault diagnosis methods, wind turbine, blade fault, machine learning.

1. INTRODUCTION

Wind energy is one of the fastest developing renewable energy assets and it is highly demand in the energy market [1]. As per statistical information from World Wind Energy Association (WWEA), 16.2% growth rate of the world's electric power supply is achieved by the wind farms in major countries (2014year-end [2]. A study report shows that wind power could reach 2,000 GW by 2030, and supply up to 17-19% of global electricity, creating over 2 million new jobs and reducing CO_2 emissions by more than 3 billion tons per year. By 2050, wind power could provide 25-30% of global electricity supply. Wind turbines are providing key contribution in the power sector in order to manage the demanding electric power supply. The wind turbines are classified as horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) [3]. The VAWT has different types they are Savonius, Darrieus and giromill [4]. To make wind energy more focused from different source of energy, performances like, accessibility, reliability, effectiveness and the life of turbines must be improved

HAWT is widely used for power generation. Generally, a wind energy framework comprises of a turbine tower which carries the nacelle and the wind turbine rotor which comprising of rotor blades and hub. Most HAWT are with three rotor blades typically placed upwind of the tower and the nacelle, as represented in Fig. 1.The nacelle is typically furnished with anemometers and a wind vane to calculate the wind rate and direction of the wind [5]. The nacelle also contains aviation light signal and the key segments of the wind turbine, i.e. the gearbox, mechanical brake, electrical generator, control frameworks, yaw drive, and so forth. The wind turbines are installed in onshore wind farms and in offshore areas and also in mountain ranges. Due to its heavy and large structure, it is very difficult to monitor the condition of the turbine components. Hence, we need a sophisticated technique which provides much diagnostics information.

Structural health condition monitoring system is very essential because structural damages may lead to dreadful damage to the framework. The structural health condition monitoring and fault diagnosis methods of the wind turbine system or its related non-ruinous testing systems are discussed in this paper. A structural health condition monitoring framework is dependable, minimal cost and incorporated into the wind turbine system may reduce wind turbine life cycle expenses and make wind energy inexpensive. The structure health condition monitoring data could be utilized as a part of a condition monitoring to minimize the time required for inspection of segments, avoid unnecessary substitution of components and to prevent down time failures [6]. Likewise, structural health condition monitoring may permit the utilization of lighter cutting edge blades that would provide higher execution of power with moderate safety. Moreover, a wind turbine with lighter blades can react to wind changes more rapidly and seize more energy. The SHCM study can be done through the following steps; (1) identification of faults, (2) fault diagnostic methods. In wind turbine, faults are occurred periodically since it is operated over time. The major faults are occurred in wind turbine are bearing faults, gear faults, brake failure, generator problem, blade fault, wind tower faults, Blade issues and much more. This paper mainly focused on the blade failure and the techniques which are implemented to reduce the downtime of the wind turbine.

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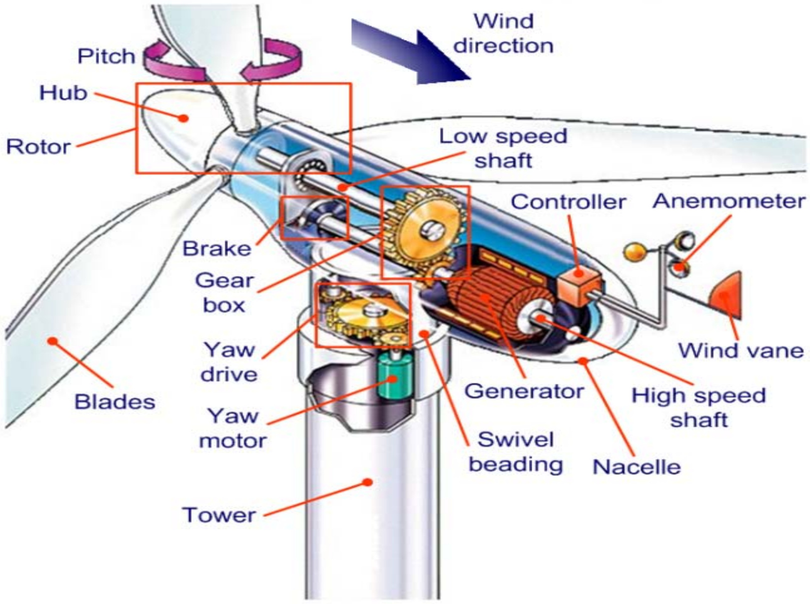

Figure-1. Structure of 3-blade HAWT.

2. BEARING FAULTS AND DIAGNOSTIC TECHNIQUE IN WIND TURBINE

Bearing is one of the important components in the wind turbine framework where this provides the smooth rotation in any weather conditions. Over the period of time they get faulty in their race and give an odd rotation to the turbine. Many researchers have done research on the bearing fault to name a few, Seyed A. Niknam *et al* [7] carried out a study on analysis of acoustic emission data for bearings subject to unbalance where they done the condition monitoring using non-destructive acoustic emission technique. They carried out with Categorical Data Analysis (CDA) and Generalized Linear Model Analysis (GENMOD) procedure to carry out their work and obtained 0.6 correlation coefficient.

Ruoyu Li and Mark Frogley [8] carried out a research on on-line fault detection in wind turbine transmission system using adaptive filter and robust statistical features. They used vibration signals and statistical parameters like kurtosis, crest factor, root mean square (RMS), impulse factor and skewness. They obtained the classification accuracy of 99.38% which is very much impressive. Nicholas Waters *et al* [9] carried out a research on targeting faulty bearings for an ocean turbine dynamometer using vibration signals. They used smart vibrations monitoring system (SVMS) in LabVIEW and predicted the classification accuracy of 74%.

3. GEARBOX FAULTS AND DIAGNOSTIC TECHNIQUE IN WIND TURBINE

The term transmission refers to the gearbox that uses gears and gear trains to give different speeds and torque. The principle of gearbox is to transmit wind power into the generator to achieve the equivalent input speed. Hence to acquire higher input speed and transmission proportion, the gearbox is primarily designed as sun and planetary gear with parallel rigging structure. Due to long-term running in poor working conditions like dust, corrosion, high storm, heavy weight, wind turbine gearbox leads to failure.

This failure leads to shaft misalignment, high oil temperature, broken shaft, shaft disproportion and so on. To avoid these failures, condition monitoring has to be carried out which can eliminate the downtime of the turbine. Many researchers have carried out research on the gearbox fault to name a few, Luisa F. Villa *et al* [10] carried out their research on angular resampling for vibration analysis in wind turbines under non-linear speed fluctuation using vibration signals. Fausto Pedro García Márquez *et al* [11] done a review on condition monitoring of wind turbine where they proposed several techniques and methods to maintain the gearbox and other parts of the wind turbine.

W.Y. Liu *et al* [12] carried out a research on a new wind turbine fault diagnosis method based on the local mean decomposition. They predicted the gear tooth crack using condition monitoring system. Yongzhi Qu [13] done a study on new acoustic emission sensor based gear fault detection approach using vibration signals. Wenyu Zhao *et al* [14] conducted research on an integrated framework of drivetrain degradation assessment and fault localization for offshore wind turbines with the help of SCADA data and classified the faults using Pattern recognition algorithm (self-organizing map (SOM) and minimum quantization error (MQE)).

Sajid Hussain *et al* [15] carried out a research on vibration analysis and time series prediction for wind turbine gearbox prognostics with the help of Adaptive neuro-fuzzy inference system (ANFIS) and Nonlinear autoregressive model with exogenous inputs (NARX).A. Lesmerises and D. Crowley *et al* [16] carried out a study on effect of different work scope strategies on wind turbine gearbox life cycle repair costs using statistical analysis. Junda Zhu *et al* [17] carried out a research on lubrication oil condition monitoring and remaining useful life prediction with particle filtering using viscosity sensor. W.Y. Liu *et al* [18] done his research on fault diagnosis on wind turbine blade, cabin and tower coupling system using vibration analysis.

Philip Cross and Xiandong Ma [19] carried out the study on nonlinear system identification for model-based condition monitoring of wind turbines using SCADA data and simulated using Xilinx. Caichao Zhu *et al* [20] done a research on dynamical characteristics of wind turbine gearboxes with flexible pins using vibration signals and FEM analysis for planetary gears. I. Antoniadou *et al* [21] conducted research on a time frequency analysis approach for condition monitoring of a wind turbine gearbox under varying load conditions using vibration signals and classified the faults using different techniques like empirical mode decomposition (EMD), Hilbert transform (HT), teager–kaiser energy operator (TKEO) and MATLAB modelling.

Aijun Hu *et al* [22] carried research on a new wind turbine fault diagnosis method based on ensemble intrinsic time-scale decomposition (EITD) and wavelet packet transform (WPT) fractal dimension. They achieved the correlation coefficient of 0.6622 in regression analysis. Silvio Simani *et al* [23] done a research on wind turbine simulator fault diagnosis via fuzzy modelling and identification techniques using vibration signals. They obtained the classification accuracy of 99.70% using fuzzy and FMEA approach. Zhipeng Feng *et al* [24] done their study on time-frequency analysis based on Vold-Kalman filter and higher order energy separation (HOES) for fault diagnosis of wind turbine planetary gearbox under non-stationary conditions using vibration analysis.

4. BRAKE FAULTS AND DIAGNOSTIC TECHNIQUE IN WIND TURBINE

One of the over-speed control methods for a wind turbine is mechanical braking. The mechanical brake is generally applied after the blade furling and electromagnetic braking (where fitted) have reduced the shaft speed. Otherwise, if lacking the mechanical brake, the component would rapidly be worn down if it is directly used to brake the turbine from full speed. Failures within the braking process, for example when the speed exceeds the limit, can cause serious damages to the main structure, especially the mechanical units and blades. Failures within the hydraulic unit will also result in the brakes remaining on and increase the downtime. Many researchers have carried out research on the brake fault especially M. Entezami *et al* [25] done a study on fault detection and diagnosis within a wind turbine mechanical braking system using condition monitoring and vibration signals. It investigates online condition monitoring based on voltages and currents for mechanical wind turbine brake system fault diagnosis. They used current signature analysis (CSA) and Simulink for diagnose the fault.

5. GENERATOR FAULTS AND DIAGNOSTIC TECHNIQUE IN WIND TURBINE

Generator can transform mechanical energy into electricity energy directly. There are kinds of generator from the structure side, such as cage induction generator, brushless doubly-fed generator, Alternating Current (AC) excited generator, synchronous generator, etc. Generator's long-term operation in the electromagnetic environment may cause some common failures such as generator excessive vibration, generator overheating, bearing overheating, abnormal noises and insulation damage, etc. Many researchers have carried out research on the generator faults; to name a few, Shuhui Li *et al* [26] done a comparative analysis on regression and artificial neural network models for wind turbine power curve estimation using benchmark data, Polynomial (Regression) and Multilayer Perceptron (MLP) algorithms. M. A. Khan and P. Pillay *et al* [27] carried out a design of a permanent magnet (PM) wind generator, optimized for energy capture over a wide operating range using simulation process.

Lin *et al* [28] done a study on intelligent controlled wind turbine emulator and induction generator system using radial basis function network (RBFN) on benchmark data. Shikha Singh *et al* [29] carried out a study on wind power estimation using artificial neural network on benchmark data. They described about the wind speed variation which affects the power output from the turbine. They used extended kalman filter training algorithm, multilayer perceptron (MLP). V. Calderaro *et al* [30] carried out a research ona fuzzy controller for maximum energy extraction from variable speed wind power generation systems using SCADA data and they used Takagi–Sugeno–Kang (TSK) fuzzy, genetic algorithms (GA) and recursive least-squares (LS) techniques in their research.

John G. Vlachogiannis [31] carried his research on probabilistic constrained load flow considering integration of wind power generation and electric vehicles using S-Model Finite Actions Learning Automata (S-FALA), Continuous Actions Learning Automata (CALA), Hybrid Learning Automata System (HLAS) and Reinforcement Learning Signals. Andrew Kusiak *et. al* [32] done a model for monitoring wind farm power using SCADA data, multi-layer perceptron algorithm (MLP), REP tree, M5P tree, bagging (bootstrapping aggregating) tree and k-nearest neighbour (k-NN) algorithm. Andrew Kusiak and Wenyan Li [33] done a work on virtual models for prediction of wind turbine parameters like power output and rotor speed using SCADA data, Boosting Tree, NN, SVM and KNN. Yüksel Oğuz and İrfan Güney [34] carried out an experiment on Adaptive neuro-fuzzy inference system to improve the power quality of variable-speed wind power generation system and simulated the faults using vibration signals and MATLAB. Pourmousavi Kani and Ardehali [35] carried out a study on very short-term wind speed prediction using benchmark data and artificial neural network–Markov chain model (ANN-MC).

Anoop Verma and Andrew Kusiak [36] have reported a research on fault monitoring of wind turbine generator brushes using SCADA data and data-mining approach such as, Tomek Links, Random Forest, Multilayered perceptron (MLP), Boosting tree, k-NN and Support vector machine (SVM) algorithms. Hany M. Hasanien and S.M. Muyeen [37] have done a work on design optimization of controller parameters used in variable speed wind energy conversion system by genetic algorithms, SCADA data and MATLAB simulation. Wenxian Yang *et al* [38] carried out a work on operational condition independent criteria dedicated to monitoring wind turbine generators. Inter-turn and open-circuit faults are simulated on the rotor and stator windings of an induction generator by using Simulink.

Meik Schlechtingen *et al* [39] carried out a comparative study on data-mining approaches for wind turbine power curve monitoring using SCADA data. They compared the techniques like cluster center fuzzy logic, k-nearest neighbour, neural network and adaptive neuro-fuzzy interference system. A. Clifton *et al* [40] carried out a study using machine learning approach to predict the wind turbine power output. They used benchmark data, regression tree by TurbSim and FAST simulation in their work for prediction. Yue Zhao *et al* [41] have done a review on position/speed sensor less control for permanent magnet synchronous machine- based wind energy conversion systems using mathematical modelling. Dalibor Petkovic *et al* [42] carried out a work on adaptive neuro-fuzzy maximal power extraction of wind turbine with continuously variable transmission using benchmark data and Simulink.

6. TOWER FAULTS AND DIAGNOSTIC TECHNIQUE IN WIND TURBINE

The tower failures seldom occur however, the various order of vibration mode may couple with the drive system and blades, which will affect the operating efficiency, service life of turbines. RaúlRuizdela Hermosa González-Carrato *et al* [43] have done their work on maintenance management of wind turbines structures via mel-frequency cepstrum (MFC) and wavelet transforms. They detected the corrosion and crack on the surface of the turbine tower using ultrasound technique and continuous wavelet transforms (CWT) and discrete wavelet transforms (DWT) methods.

7. BLADE FAULTS AND DIAGNOSTIC TECHNIQUE IN WIND TURBINE

The wind makes the rotor blades turn, thus making the shaft inside the wind turbine turn. The thin, long and elastic blade is the component suffering the most complex force. It is easy to cause vibration, and all the exciting forces are transformed by the blades. The frequent and violent vibration will lead to the crack of blade, last to breakdown. The blade is one of the components with frequent failure. Unfortunately, because of the structure and working condition, the vibration of the blade is difficult to measure on line. Distributed temperature and strain sensors have been developed for structural monitoring. Many researchers have carried out research on the blade faults; to name a few, W.Q. Jeffries *et al* [44] carried out an experience with bicoherence of electrical power for condition monitoring of wind turbine blades using vibration data. They made a flap wise bending to the blade and simulated using MATLAB. Mahmood M. Shokrieh and Roham Rafiee *et al* [45] carried out a study on simulation of fatigue failure in a full composite wind turbine blade using vibration signals. They done a static analysis and simulated using ANSYS and predicted the average life of a blade is 21-33 years. Anne Jüngert *et al* [46] carried her work on damage detection in wind turbine blades using two different acoustic techniques namely local resonance spectroscopy and ultrasound-echo technique. She discussed about the fault created on blade due to delamination and how this non-destructive technique (NDT) used to find the damage area.

Xiang Gong and Wei Qiao [47] have conducted a simulation investigation of wind turbine imbalance faults by creating a pitch angle twist and weight loading on the blade and they simulated using continuous wavelet transform in Simulink. François Besnard and Lina Bertling [48] have studied an approach for condition-based maintenance optimization applied to wind turbine blades using benchmark data. This approach is applicable to the inspection based maintenance like visual inspection, ultrasonic inspection, thermography inspection and fiber optic based inspection.

Fangfang Songa *et al* [49] have conducted the experiment on optimization design, modelling and dynamic analysis for composite wind turbine blade and simulated using ANSYS and FEM analysis. Andrew Kusiak and Anoop Verma [50] have built a data-driven approach for monitoring blade pitch faults in wind turbines using SCADA data. They altered the blade angle asymmetry and classified using bagging, neural network (NN), PART, K-nearest neighbor, genetic programming (GP). They obtained the accuracy of 74.7%, Sensitivity of 75.3% and Specificity of 80.5%. Nassim Laouti *et al* [51] have carried out a study on fault detection in wind turbines using support vector machines (SVM) and radial basis function (RBF) was used as Kernel. Andrew Kusiak and Zijun Zhang [52] carried out a study on adaptive control of a wind turbine with data mining and swarm intelligence using SCADA data. They created a pitch angle twist on blade and classified the fault using particle swarm fuzzy algorithm.

Abdelnasser Abouhnik and Alhussein Albarbar [53] studied on wind turbine blades condition assessment based on vibration measurements and the level of an empirically decomposed feature using ANSYS. P. Malhotra *et al* [54] have conducted a review and design study of blade testing systems for utility scale wind turbines using vibration signals and NDT tri-axial testing method. U.I.K. Galappaththi *et al* [55] carried out an analysis of the effect of defects for fatigue life of composite wind turbine blades using FEM data and ANSYS software. Their prediction was 20% reduction of fatigue life and 30% near to the root of the wind turbine blade. Asis Sarkar and Dhiren Kumar Behera [56] have

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done a work on wind turbine blade efficiency and power calculation with electrical analogy using FEM analysis and predicted power efficiency of 30% at tip speed ratio (TSR) of 11.6.

Almukhtar [57] has carried his experiment on effect of drag on the performance for an efficient wind turbine blade design using MALAB by creating twist on blade. A. Staino *et al* [58] conducted research on actuator control of edge wise vibrations in wind turbine blades using up and down method. Branko M. Radicevic *et al* [59] done a work on impact of wind turbine blade rotation on the lightning strike incidence on a theoretical and experimental study using a reduced-size model. This also carried out using up and down method. Mohamed A. Sayed *et al* [60] carried a study on aerodynamic analysis of different wind turbine blade profiles using finite volume method, computational fluid dynamics (CFD), Reynolds-averaged-navier–stokes (RANS) equations.

Peter J. Schubel and Richard J. Crossley [61] have designed a wind turbine blade and reviewed the current state of art for wind turbine blade design, including theoretical maximum efficiency, propulsion, practical efficiency, HAWT blade design, and blade loads by AERODYN. Secil Varbak Nese *et al* [62] carried out a work on analysis of wind turbine blade deformation with short time Fourier transform (STFT) method using vibration signals. Susan A. Frost *et al* [63] has done a study on integrating structural health management with contingency control for wind turbines using nonlinear high fidelity simulation and achieved 90% accuracy in their work. Jamie L. Godwin and Peter Matthews [64] done classification and detection of wind turbine pitch faults through SCADA data analysis and RIPPER algorithm which yield them 87.05% classification accuracy in pitch angle fault.

Dylan D. Chase *et al* [65] carried out a research on detection of damage in operating wind turbines by signature distances estimating the blade damage by dynamic response using vibration data. Dynamic responses are transformed to surfaces via continuous wavelet transforms (CWT) to accentuate the effect of wind or damage on the dynamic response. Shigeru Yokoyama [66] done a study on lightning protection of wind turbine blades and suggested some material selection for blade. Yinghui Li *et al* [67] have carried out a work on dynamic characteristics of lag vibration of a wind turbine blade using FEM analysis.

P.J. Schubel *et al* [68] done a review on structural health and cure monitoring techniques for large wind turbine blades using Dielectric, acoustic, ultrasonic, thermal and fibre optic monitoring methods. They proposed Fibre Bragg Gratings (FBG) was the better method when compared with other monitoring method. Neil Buckney *et al* [69] carried out a study on structural efficiency of a wind turbine blade and proposed alternative structural layouts for wind turbine blades in their design, minimizing weight and reducing the cost of wind energy. Bindi Chen *et al* [70] conducted an experiment on wind turbine pitch faults prognosis using a-priori knowledge based adaptive neuro-fuzzy inference system (ANFIS) using SCADA data and obtained 88.30% classification accuracy.
Sabbah Ataya and Mohamed M.Z. Ahmed [71] have carried out a study on damages of wind turbine blade trailing edge by their forms, location and root causes using vibration signals. The location detection of the crack in the blade (longitudinal cracks and transverse cracks) and the work life of the blade was discussed using visual inspection method. The average life time was predicted to be 17-22 years for 100/300kW blade. Jui-Sheng Chou *et al* [72] have conducted failure analysis of wind turbine blade under critical wind loads using vibration data and ANSYS. Erin E. Bachynskia *et. al* [73] have done a dynamic analysis of floating wind turbines during pitch actuator fault, grid loss, and shutdown using generalized dynamic wake (GDW) simulation.

Bin Yang and Dongbai Sun [74] made a survey on testing, inspecting and monitoring technologies for wind turbine blades including mechanical property testing, non-destructive testing/inspecting (infrared thermography and X-ray imaging), full-scale testing, structural health monitoring and condition monitoring using acoustic and vibration signals. Gabriele Bedon *et al* [75] carried out optimization of a darrieus vertical axis wind turbine using blade element momentum theory (BEM) and evolutionary algorithm. Xiongwei Liu *et al* [76] studied on optimized linearization of chord and twist angle profiles for fixed pitch, fixed speed wind turbine blades through adopting linear radial profiles of the blade chord and twist angle and optimizing the slope of these two lines using blade element momentum (BEM) theory and annual energy production (AEP) calculation.

Dalibor Petković *et al* [77] studied on adaptive neuro-fuzzy approach for wind turbine power coefficient estimation using vibration data and MATLAB simulation. N. Dervilis *et al* [78] carried out a research on damage diagnosis for a wind turbine blade using pattern recognition such as principal component analysis (PCA), nonlinear principal component analysis (NLPCA), artificial neural network (ANN), auto-associative neural network (AANN) and Radial Basis Functions (RBF) using vibration signals. Sungmin Kim *et al* [79] done a study on identifying cracks in wind turbine blades undergoing operational loads using the vibro-acoustic modulation technique. Omar Mabrok Bouzid *et al* [80] carried out a work on structural health monitoring of wind turbine blades using acoustic source localization and wireless sensor networks obtained error rate of 7.98% in their work. Christopher Niezrecki *et al* [81] have done a work on wind turbine blade health monitoring using acoustic beamforming techniques. Y.M. Ji and K.S. Han [82] had done a work on fracture mechanics approach for failure of adhesive joints in wind turbine blades using vibration signals and FEM.

Yanfeng Wang *et al* [83] have done a work on damage detection method for wind turbine blades based on dynamics analysis (FEM) and mode shape difference curvature information (MSDC). J. Zangenberg *et al* [84] made a design of a fibrous composite preform for wind turbine rotor blades and suggested a selection of material for blade. Xiao Chen *et al* [85] carried out a study on preliminary failure investigation of a 52.3 m glass/epoxy composite wind turbine blade using visual inspection and suggested the composite material. Yan Li *et al* [86] have done an experimental study in icing on wind turbine blade air foil. They done mathematical calculation for icing rate, blade angle and icing area due to bad weather and predicted icing rate of NACA7715 is 6.6%, and the maximum icing area ratio is 21.8% at the attack angle of 80^0.

Fabio Agnese and Fabrizio Scarpa [87] have done a study on macro-composites with star shaped inclusions for vibration damping in wind turbine blades using dynamic mechanical analyzer (DMA), shear dynamic test (SDT). H.F.Zhou *et. al* [88] have carried out a review on full-scale structural testing of wind turbine blades using acoustic signal and done with X-Ray (NDT), photo grammetry and digital image correlation (DIC). Ashwani Kumar *et al* [89] have done work on free vibration analysis of AL 2024 wind turbine blade based on FEA and vibration signals. Hemaraju Pollayi and Wenbin Yu [90] carried out a study on modelling matrix cracking in composite rotor blades within variational asymptotical beam sectional analysis (VABS) framework. They also done the modelling along with geometrically exact beam theory (GEBT) and achieved the accuracy of 92.4%.

Perry Roth-Johnson *et al* [91] have carried out a structural design of spars for 100-m biplane wind turbine blades. Several spars were designed to approximate the Sandia SNL100-00 blade ("monoplane spar") and the biplane blade ("biplane spar"). They concluded the biplane spar configurations have 25-35% smaller tip deflections and 75% smaller maximum root bending moments than monoplane spars of the same length and mass per unit span. Panu Pratumnopharat *et al* [92] carried out a work on wavelet transform based stress time history editing of horizontal axis wind turbine blades using vibration signals. They used time correlated fatigue damage (TCFD), mexican hat wavelet (Mexh), meyer wavelet (Meyr), daubechies 30th order (DB30), morlet wavelet (Morl) and discrete Meyer wavelet (Dmey) as a diagnostic method and obtained TCFD - 89.82%, Morl - 80.34%, Meyr - 79.76%, Dmey - 80.30%, Mexh - 79.23%, DB30 - 80.81%.

C.G. Gebhardt and B.A. Roccia [93] done a work on nonlinear aero elasticity as an approach to compute the response of three blade large scale horizontal axis wind turbines using FEM analysis. Kendra L. Van Buren *et al* [94] made a study on model selection through robustness and fidelity criteria for modelling the dynamics of the CX-100 wind turbine blade using FEM. Chad Van der Woude and Sriram Narasimhan [95] carried a study on vibration isolation for wind turbine structures depends on vibration and simulated using ANSYS. Jianping Zhang *et al* [96] carried out their work on the influence of wind shear on vibration of geometrically nonlinear wind turbine blade under fluid structure interaction using ANSYS. Hamed Badihi *et al* [97] have done their work on fuzzy gain scheduled active fault tolerant control of a wind turbine using vibration data.

Amr M. Abd-Elhady *et al* [98] carried out an experimental evaluation of air termination systems for wind turbine blades reported in IEC-61400-24 standard using up and down method. Erick Y. Gómez U. *et al* [99] have done a design and manufacturing of wind turbine blades of low capacity using CAD/CAM techniques and composite materials. Shahaboddin Shamshirband *et al* [100] carried out a comparative study on wind turbine power coefficient estimation by soft computing methodologies using polynomial and radial basis function (RBF) which are applied as the kernel function of support vector regression (SVR). They obtained the correlation coefficient of 0.997 using vibration signals.

Peyman Poozesh *et al* [101] carried out a full field inspection of a utility scale wind turbine blade using digital image correlation on a 50mutility scale blade subjected to quasi static and cyclic loading. Mark Mollineaux *et al* [102] have done a work on damage detection methods on wind turbine blade testing with wired and wireless accelerometer sensors using benchmark data and autoregressive moving average (ARMA) and Continuous Wavelet Transform (CWT) used as modelling techniques. Mahmood Shafiee *et al* [103] have carried out a work on an opportunistic condition based maintenance policy for offshore wind turbine blades subjected to subjected to stress corrosion cracking and environmental shocks and simulated using MATLAB. H.M. Slot *et al* [104] have conducted a review of coating life models on leading edge erosion of coated wind turbine blades and they suggested the material and prediction of the life time of the blade. Shizhong Zhang *et al* [105] carried out a design and analysis of jet based laboratory equipment for performance evaluation on erosion of wind turbine blade coatings. Olga Bitkina *et al* [106] have carried out an experimental and theoretical analysis of the stress strain state of anisotropic multilayer composite panels for wind turbine blade using Kirchhoff hypotheses and Cauchy equations on FORTRAN Software.

Mahmudur Rahman *et al* [107] conducted a review on performance enhancement of wind turbine systems with vibration control using Tuned mass damper (TMD), Tuned liquid damper (TLD), Controllable fluid damper (CFD). Rajkumar. P *et al* [108] have done a work on increasing the impact testing of wind turbine blade with wire string. This paper describes about the design of material for high velocity wind and low weight material of the turbine blade. A. C. Benim *et al* [109] carried out a work on optimization of air foil profiles for small wind turbines with emphasis on stable performance under highly unstable wind conditions using Mesh Adaptive Direct Search (MADS) optimization algorithm and obtained 39% of prediction accuracy. O. Al-Khudairi and H. Ghasemnejad [110] have carried out a work to improve failure resistance in joint design of composite wind turbine blade materials using cohesive zone modelling (CZM).

Jae-Kyung Lee *et al* [111] have carried out a work on transformation algorithm of wind turbine blade moment signals for blade condition monitoring using vibration signals. Hossein Habibi *et al* [112] done work on a dual de-icing system for wind turbine blades combining high power ultrasonic guided waves and low frequency forced vibrations. This either prevents ice accumulation (anti-icing) or removes any ice layer present on the surface of the blade material (de-icing). Mohammad M. Rezaei *et al* [113] have carried out a development of a reduced order model for nonlinear analysis of the wind turbine blade dynamics using Galerkin method, reduced order model and FEM analysis. Xiang Li *et al* [114] carried out a research on crack growth sparse pursuit for wind turbine blade using vibration data and lamb wave propagation, sparse reconstruction approach, growth sparse pursuit, CoSaMP Algorithm were used as a modelling techniques. Wei Xie *et al* [115] have made a novel folding blade of wind turbine rotor for effective power control using MATLAB and achieved maximum reduction of 51.1% compared to pitch control and Optimum fold angles of 55^0 and 90^0.

R. Saravanakumar *et al* [116] have done a work on validation of an integral sliding mode control for optimal control of a three blade variable speed variable pitch wind turbine using simulation. This paper mainly focuses on the control of variable speed variable pitch wind turbine (VSVPWT) for maximization of extracted power at below rated wind speed and regulation of extracted power when operating at above rated wind speed. Manudha T. Herath *et al* [117] have made a design of shape adaptive wind turbine blades using differential stiffness bend twist coupling using genetic algorithm (GA) and FEM Analysis. Chao Liu *et al* [118] have conducted a study on influence of alternating loads on nonlinear vibration characteristics of cracked blade in rotor system using vibration data and FEM. Shizhong Zhang *et al* [119] studied on rain erosion of wind turbine blade coatings using discrete water jets and the effects of water cushioning, substrate geometry, impact distance, and coating properties of the blade using image processing.

R.H. Barnes *et al* [120] have done an improved methodology for design of low wind speed specific wind turbine blades using FEM and ANSYS. This paper tells the expectation that the standard high wind speed design process results in less efficient structures when used for low wind speed conditions, and that a low wind speed specific design process is able to yield structural improvements. Khazar Hayat and Sung Kyu Ha [121] carried out a work on load mitigation of wind turbine blade by aero elastic tailoring via unbalanced laminates composites and simulated using classical laminate theory and blade element momentum. Victor Maldonado *et al* [122] have done a work on the role of free stream turbulence with large integral scale on the aerodynamic performance of an experimental low Reynolds number S809 wind turbine blade using numerical integration method. Simon Hoell and Piotr Omenzetter [123] have carried out a structural damage detection in wind turbine blades based on time series representations of dynamic responses using vibration data and cross-correlations, principal component analysis (PCA), genetic programming (GP) as the diagnostic algorithm.

Wang Yongzhi *et al* [124] carried out a study on composite wind turbine blade aerodynamic and structural integrated design optimization based on radial basis function (RBF) meta-model, blade element momentum (BEM) theory, finite element method (FEM) and multi-island genetic algorithm (MIGA). This paper aims to reduce the mass of blade under some constraints, including the power and deflection at the rated wind speed, and the strength and deflection under ultimate case. P.U. Haselbach *et al* [125] have studied on the effect of delamination on local buckling in wind turbine blades using FEM analysis. They simulated by bending the blade in flap wise and conducted the experiment.

8. ESSENTIAL METHODS FOR OVERALL MONITORING OF WIND TURBINE

Many researchers come up with different technique for SHCM and many FDM were also developed. Some techniques like wavelets [126-128] are very much useful in predicting the faults since they are well localized in both time and frequency domains. Machine learning technique [129-132] is study of pattern recognition and computational learning theory in artificial intelligence. Machine learning explores the study and construction of algorithms that can learn from and make predictions on data. It has strong ties to mathematical optimization [133-136], which delivers methods, theory and application domains to the field. Simulation process are widely used in condition monitoring [137-143] to design and development of faults. Statistical analyses [144-147] are also carried to determine the mathematical assumption and study of the collection, analysis, interpretation, presentation, and organization of data. Non-destructive testing (NDT) [148-150] is a techniques used in industry to evaluate the properties of a material, component or system without causing damage. NDT does not permanently alter the article being inspected; it is a highly valuable technique that can save both money and time in product evaluation, troubleshooting, and research. These different techniques are very much useful in SHCM where they can able to reduce the down time of the wind turbine.

9. CONCLUSIONS

Although many techniques existing in other industries can be directly or indirectly applied, wind turbines present particular challenges for successful and reliable diagnostics and prognostics.At first, the typical structure and failures of every component in wind turbine are discussed in detail along with the techniques used in the resent years. Then, some essential techniques were discussed to give a clear idea of choosing the technique to diagnose the fault. In future, these techniques may also be combined with each other to provide a better result for the fault prediction and to carry out a best fault diagnosis method for the SHCM of wind turbine.

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