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Condition Monitoring of Wind Turbines: A Review

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CONDITION MONITORING OF WIND TURBINES A REVIEW

Strictly as per the compliance and regulations of :

Condition Monitoring of Wind Turbines: A Review

Sachin Sharma [α] & Dalgobind Mahto [σ]

Abstract - This paper presents condition monitoring in wind turbines, and related technologies currently applied in practice and under development for aerospace applications, are reviewed. Condition monitoring system estimate the current condition of a machine from sensor measurements, whereas prediction systems give a probabilistic forecast of the future condition of the machine under the projected usage conditions. Current condition monitoring practice in wind turbine rotors involves tracking rotor imbalance, aerodynamic, surface roughness and overall performance and offline and online measurements of stress and strain.

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I. Introduction

Condition based maintenance has been described as a process that require technologies and people skills that integrates all available equipment condition indicators to make timely decisions about maintenance requirement of important equipment. Today most of the maintenance actions are carried out either by preventive maintenance or corrective maintenance approach. The preventive maintenance generally have fixed intervals to prevent the components from failure where as corrective maintenance is performed after a fault or breakdown has occurred. But these approaches proves very costly in many cases due to loss in production, cost of keeping spare parts , quality deficiencies etc. Condition based maintenance involves the measurement or monitoring of specific parameters which directly corresponds to machine. The main difference between preventive maintenance and condition based maintenance is that condition based maintenance uses various methods of monitoring for checking the condition of the machine to determine the actual mean time for failure where as preventive maintenance depends upon industrial average life statistics. Condition based maintenance has three complimentary levels of implementations:

i. Data acquisition step, to obtain data relevant to system health.
ii. Data processing: Data processing analyze the data for interpretation, also known as Diagnosis.
iii. Maintenance decision making step, to implement best optimum maintenance policy (Prognosis).
iv. This methodology as having existed for many years. Thus methodology is recently developed and has evolved over the past three decades from precursor maintenance methods.

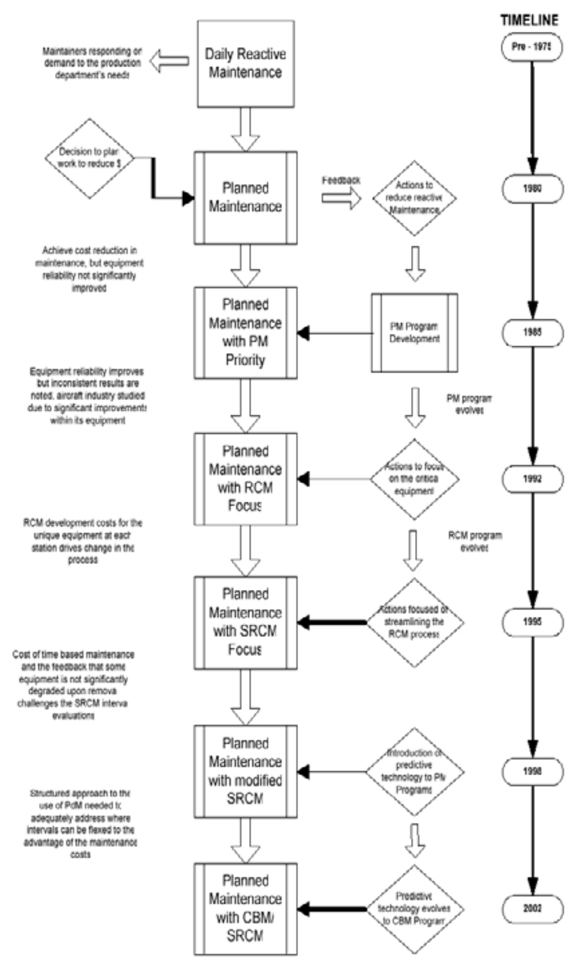

Figure 1.1 : Evolution of condition based maintenance

On the basis of data acquisition and periodicity analyses machine protection system can be of folowing types:

a. OFFLINE system: In this type of system the vibration specialists and maintenance managers determine the system for periodic maintenance of machines , mean data acquisition and analyses based on the time base. The periodicity of data acquisition and analyses is determined by analyzing the current vibration level of machine.

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b. ONLINE system:The permanently installed systemfor vibration signals acquisition and analyses must be an online system. In ONLINE system condition monitoring units continuously monitor the vibration as well as other process variables, to trend the condition of the equipment and assist in determining when it should be removed from the service for repair. They run as stand alone davice and periodicaly transfer measured data to storage computer. Then it trigger a alarm automaticaly to plant control system and generate a e- mail message. These systems are capable of automatically communicating through a variety of methods, from earthnet GSM modem and allow monitoring of remote locations anywhere in the world.

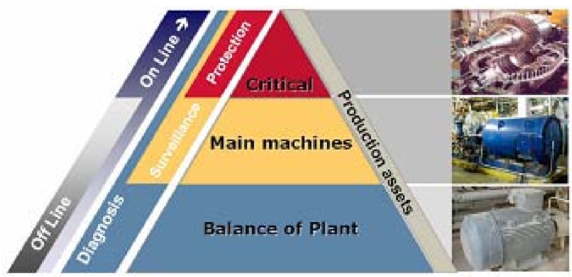

Figure1.2 : Different approaches to condition based maintenance for different equipment in the plan

Figure 1.3 : Online condition monitoring

Figure 1.4 : Handheld data collector system

c. Remote Condition Monitoring System: In REMOTE condition monitoring machines the traditional way of collecting data on site is replaced with web based maintenance equipment and it gathers the data fast and data acquisition and data transfer is cheap. By introducing a high speed computer network into vibration monitoring system, vibration signals can be transferred into a specific database. Using this data maintenance managers and vibration specialists have a real time insight into a machine's condition. Web based condition monitoring can be applied to both OFFLINE and ONLINE monitoring system. However it is generally applied to ONLINE system and in case of OFFLINE system means only remote database and vibrations specialists while the presence of maintenance personnel on site is still required for purpose of vibration data collection.

II. Objectives of CBM

CBM is performed to serve the following purposes:

- To identify the fault in the monitored object.
- To identify nature of fault.
- To determine the time up to which machine can serve without interruption before breakdown.
- To determine the degrading components.
- The core objectives of condition based maintenance are:
- To take necessary action before breakdown.
- To reduce the maintenance overhead costs.
- To perform maintenance when required.
- To reduce number of breakdowns and failure frequency rate.

II. How to Start Condition based Maintenance

One of the most attractive as pect of CBM is the fact that it can be implemented in a relatively inexpensive, step by step approach. Because condition based maintenance is based on equipment oriented concepts of predictive maintenance, it can be applied gradually one system a time.

Following steps are involved in condition based maintenance:

a) Phase 1

i. Data collection and storage procedure

Maintenance data and its uses creates the main key differences between the classical and modern maintenance methods. In past, a little attention was paid for the comparison and trending and the data was collected from maintenance results from any given interval which had been filed by reviewing. Trending and statistical analyses are the fundamental building blocks of CBM. By comparing data absolute values and data deviations via statistical analyses provide information never before available. Thus a statistically relevant data base is required. There are a lot of maintenance management software available which have same basic purpose and design are similar from one manufacturer to other. Fundamental equipment information is stored in a detailed manner. Information such as size, date of purchase, ratings, cost, maintenance cycle etc. are stored. Many power system operators have kept good paper records over the years. These paper records may be converted into computerized database which is time consuming but simple.

ii. *failure and outage information Equipment*

To access the risk of condition based maintenance program, compilation of this outage data is needed,. This information include items such as type of outage data, cause, length, cost, date etc. The condition based maintenance program implementation sequence can be prioritize by using this outage information. Equipment with high failure rate should be enrolled in the program first.

iii. *Equipment Database*

The equipment database is developed in parallel with other databases. The equipment database may be linked with master maintenance database. But more reliability is realized if they are kept separate.

iv. *Preliminary budget and plan*

The preliminary budget and planning is the final step in phase 1.Table 3.1 shows the steps include in preliminary plan.

Table 3.1 : Steps involved in preliminary plan

Field#	Linked to	Result	Comments
1	4	2	Dimensions of result depend on specific test
2	5	4.5%	
3	6	1	
4	Etc		

b) Phase 2

Information generated in phase 1 will be put to work as a living,, active CBM program.

i. *Develop detailed evaluation criteria and methods*

Based on test result data gathered in phase 1, the development of control chart strategies and other statistical evaluation techniques should begun. The exact nature of which strategies should be used may not be immediately apparent. Two options are available as shown in table 3.2.

Table 3.2 : Evaluation criteria options

1	Contract with CBM consultant for statistical criteria implementation
2	Start simple. Use graphical trending in spreadsheet.

Contracting with qualified CBM consultant, who can assist in selection and implementation of appropriate strategies. Starting simple with a commercially available spreadsheet may not be as rigorous or technically satisfying as more sophisticated statistical analyses, it may well provide a satisfactory compromise between competing technical and economic factors.

ii. *Finalize recommended maintenance procedure and intervals*

Maintenance procedure can be added as needed in future intervals, Using transformer as an example table 3.3 lists typical, predictive results, types of tests that might be used. The opinion and observations of skilled technicians are extremely important in overall evaluation.

iii. *Test reporting forms /or software*

Test forms have been around for as long as electrical equipment, virtually ever test technician has, at one time or another, created his her own form. Two approaches are now available

a. *Printed paper form*

Such forms are available from a number of sources. These preprinted forms have limitation that they need modification and manual transfer of data into various computer databases.

b. *Direct computer entry*

If a user friendly interface for the database has been designed, a mini version may be taken into the field by maintenance technicians. After such test the technician can keyboard the results directly into computer.

IV. Condition Monitoring of Wind Turbines

A Change in process parameter is an indicative of a developing failure [86]. A modern condition monitoring system consist of sensors and a processing unit which continuously check and record the condition of the component. There are various techniques to access the component condition. These techniques include vibration analyses, acoustics, oil analyses, strain measurement, and thermography. In case of wind turbine these techniques are used to monitor the major components such as blades, gear box, tower, bearings etc. A condition monitoring may be ONLINE or OFFLINE. A ONLINE monitoring provide instantaneous feedback of condition while OFFLINE provide data collected at regular intervals. For a fast fault detection while the component is in operation require good data acquisition system and appropriate signal processing. Maintenance tasks may be planned and scheduled with great efficiency which increase the reliability, safety and maintainability of the system and reduce the downtime and operational costs [87]. Therefore CM techniques are widely adopted by the industry [88,89] and its most benefits are used in offshore wind farms [90].

V. Condition Monitoring Techniques

The following techniques, available from different applications, which are possibly applicable for wind turbines, have been identified:

Vibration analysis

1. Oil analysis
2. Thermography
3. Physical condition of materials
4. Strain measurement
5. Acoustic measurements
6. Electrical effects

7. Process parameters
8. Visual inspection
9. Performance monitoring
10. Self diagnostic sensors

a) Vibration Analysis

Vibration analysis is the most known technology applied for condition monitoring, especially for rotating equipment. The type of sensors used depend more or less on the frequency range, relevant for the monitoring:

- Position transducers for the low frequency range
- Velocity sensors in the middle frequency area
- Accelerometers in the high frequency range
- And SEE sensors (Spectral Emitted Energy) for very high frequencies (acoustic vibrations)

Examples can be found for safeguarding of:

1. Shafts
2. Bearings
3. Gearboxes
4. Compressors
5. Motors
6. Turbines (gas and steam)
7. Pumps

For wind turbines this type of monitoring is applicable for monitoring the wheels and bearings of the gearbox, bearings of the generator and the main bearing. Signal analysis requires specialised knowledge. Suppliers of the system offer mostly complete systems which includes signal analysis and diagnostics. The monitoring itself is also often executed by specialised suppliers who also perform the maintenance of the components. The costs are compensated by reduction of production losses. Application of vibration monitoring techniques and working methods for wind turbines differ from other applications with respect to:

- The dynamic load characteristics and low rotational speeds In other applications, loads and speed are often constant during longer periods, which simplifies the signal analysis. For more dynamic applications, like wind turbines, the experience is very limited.
- The high investment costs in relation to costs of production losses. The investments in conditions monitoring equipment is normally covered by reduced production losses. For wind turbines, especially for land applications, the production losses are relatively low. So the investment costs should for a important part be paid back by reduction of maintenance cost and reduced costs of increased damage.

b) Oil Analysis

Oil analysis may have two purposes:

- Safeguarding the oil quality (contamination by parts, moist)

Safeguarding the components involved (characterisation of parts) Oil analysis is mostly executed off line, by taking samples. However for safeguarding the oil quality, application of on-line sensors is increasing. Sensors are nowadays available, at an acceptable price level for part counting and moist. Besides this, safeguarding the state of the oil filter (pressure loss over the filter) is mostly applied nowadays for hydraulic as well as for lubrication oil. Characterisation of parts is often only performed in case of abnormalities. In case of excessive filter pollution, oil contamination or change in component characteristic, characterisation of parts can give an indication of components with excessive wear.

c) Thermography

Thermograhy is often applied for monitoring and failure identification of electronic and electric components. Hot spots, due to degeneration of components or bad contact can be identified in a simple and fast manner. The technique is only applied for of line usage and interpretation of the results is always visual. At this moment the technique is not interesting for on line condition monitoring. However cameras and diagnostic software are entering the market which are suitable for on-line process monitoring. On the longer term, this might be interesting for the generator and power electronics.

d) Physical condition of materials

This type of monitoring is mainly focussed on crack detection and growth. Methods are normally off line and not suitable for on line condition monitoring of wind turbines. Exception might be the usage of optical fuses in the blades and acoustic monitoring of structures.

e) Strain Measurement

Strain measurement by strain gauges is a common technique, however not often applied for condition monitoring. Strain gauges are not robust on a long term. Especially for wind turbines, strain measurement can be very useful for life time prediction and safeguarding of the stress level, especially for the blades. More robust sensors might open an interesting application area. Optical fibre sensors are promising, however still too expensive and not yet state-of-the-art. Availability of cost effective systems, based on fibre optics can be expected within some years. Strain measurement as condition monitoring input will than be of growing importance.

f) Acoustic Monitoring

Acoustic monitoring has a strong relationship with vibration monitoring. However there is also a principle difference. While vibration sensors are rigid mounted on the component involved, and register the local motion, the acoustic sensors "listen" to the component. They are attached to the component by flexible glue with low attenuation. These sensors are successfully applied for monitoring bearing and gearboxes.

There are two types of acoustic monitoring. One method is the passive type, where the excitation is performed by the component itself. In the second type, the excitation is externally applied.

g) Electrical Effects

For monitoring electrical machines MCSA (Machine Current Analysis) is used to detect unusual phenomena. For accumulators the impedance can be measured to establish the condition and capacity. For medium and high voltage grids, a number of techniques are available:

- Discharge measurements
- Velocity measurements for switches
- Contact force measurements for switches
- Oil analysis for transformers

For cabling isolation faults can be detected. These types of inspection measurements do not directly influence the operation of the wind turbines.

h) Process Parameters

For wind turbines, safeguarding based on process parameters is of course common practice. The control systems become more sophisticated and the diagnostic capabilities improve. However safeguarding is still largely based on level detection or comparison of signals, which directly result in an alarm when the signals become beyond predefined limit values. At present, more intelligent usage of the signals based on parameter estimation and trending is not common practice in wind turbines.

i) Performance Monitoring

The performance of the wind turbine is often used implicitly in a primitive form. For safeguarding purposes, the relationship between power, wind velocity, rotor speed and blade angle can be used and in case of large deviations, an alarm is generated. The detection margins are large in order to prevent for false alarms. Similar to estimation of process parameter, more sophisticated methods, including trending, are not often used.

VI. Possible Applications of Condition Monitoring

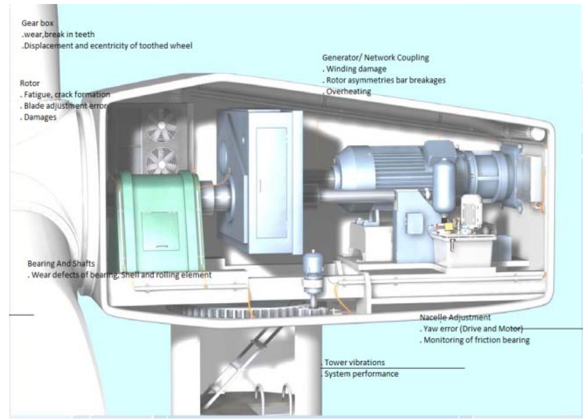

Figure 6.1 : Applications of condition monitoring in wind turbine

a) Gear Box

i. Wear, break in teeth
ii. Displacement and eccentricity of toothed wheels

b) Rotor

i. Fatigue crack formation
ii. Blade adjustment error
iii. Damages (via lightening strike)

c) Generator network coupling

i. Winding damage
ii. Rotor asymmetries, bar breakage
iii. Overheating

d) Bearing and Shafts

i. Wear, defects of bearings shells and rolling elements
ii. Fatigue crack formation in shafts

e) Tower vibration

i. System performance
ii. Environmental influences
iii. Crack formation, fatigue

f) Nacelle adjustment

i. Yaw error (Drive & motor)
ii. Monitoring of friction bearing

VII. Literature Review

Palle Christensen and Gregor Gie bel (2001) [1] introduces a new condition monitoring tool which provide a fully automatic supervision and control of the wind farm on internet and data can be accessed with common interface for all form of data from farm.

T Holroyd (2001) [2] constructed a test rig to seeded the defect of varying sizes on outer races of bearing. A comparison has been done between AE (Acoustic Emission) and vibration analyses. It was concluded that AE not even detect earlier faults but can also provide indication of defect size.

N. Jamludin et al. (2001) [3] present a work in which they apply the stress waves analyses to detect early stages damages of bearing at a very low speed i.e. 1.12r/min.

Shjn Dander (2002) [4] presented a work in which they access the use of time domain model based fault detection and identification (FDI) method for application to a horizontal axis wind turbine (HAWT) that uses pitch to vane control. They use two approaches, the system identification approach and observer based approach using the kalman filter. They construct a horizontal axis wind turbine model and use the simulation to test various approaches. Two algorithms based on kalman filter are presented which provide a reliable estimate of the wind speed by including it in an augmented system state.

T.W. Verbruggen (2003) [5] develop a inventory of available condition monitoring techniques and selecting a set which has added a value for wind turbines. The area for further development of sensors, algorithm for data analyses were investigated.

L. Mihet-Popa et al (2003) [6] proposed a technique based on steady state analyses and applied to induction generators. This technique identify interturn stator fault and rotor asymmetries.

L. W. M.M. Rademakers et al. (2004) [7] they present a condition monitoring system for fiber optic blades. They installed the system on a NORDEX turbine for about one year to get operational experience with it to optimize and extend the algorithm. The data is stored on turbine module with back up at ECN. Based on this historical data algorithm were tested before implementing on any turbine system.

Giurgiutiu, V & Cuc, A. (2005) [8] presented a damage detection method which was based on ultrasonic rely due to propagation and reflection of elastic waves within the material. They identify local damages and flaws via blade field disturbances. They propose the use of piezoelectric transducer in place of conventional non destructive transducer because piezoelectric transducer can act both transmitter and receiver of ultrasonic waves.

Douglas H. (2005) [9] presented a work in which a steady state technique has been applied e.g. Motor Current Signature Analyses (MCSA) and Extended Park's Vector Approach (EPVA) and a new technique which was combination of EPVA and discrete wavelet transform and statics to detect the turn faults in doubly fed induction generators (DFIG). The proposed technique shows that steady state technique is not effective when DFIG's operate under transient condition but stator turn faults can be detected under transient conditions.

Christopher A. Walfard (2006) [10] highlights the relevant issues of reliability for wind turbine power generation projects. They identify the cost elements associated with wind farm operation and maintenance. Causes of uncertainty in reliability estimation of wind turbine was also discussed.

C. Walfard, D. Robert (2006) [11] present a work in which they conduct a cost benefit analyses and estimates that cost liability for failure of wind turbine after four to five years is $75,000 to $ 2,25,000 per event for megawatt scale turbine.

R.W. Hyers et al. (2006) [12] compare the condition monitoring in wind turbine with monitoring and prognosis in helicopter gearboxes. They evaluate the state of art of electronic control and power electronics and compare with state of art in aerospace.

Jesse A. Andrawus et al. (2006) [13] apply the RCM approach to horizontal axis wind turbine to detect various failure modes and their causes and effects on system operation. The failure consequences are estimated in term of financial terms by evaluation. Over the whole life cycle of wind turbine the CBM activities are identified and assessed to maximize the return on investment in wind farms.

David Mc Millan and Grahm W. Ault (2007) [14] measure the benefits of condition monitoring quantitatively. They construct a probabilistic model which uses various methods including discrete-time Markov Chains, Monte Carlo method and time series modeling.

Ayetullah Gunel et al. (2007) [15] present a new technique i.e. fluid condition monitoring system in which temperature of oil filter and cooling subsystems are monitored with various sensors. The other parameters such as absolute pressure drop across the filter, dielectric constant and viscosity are also monitored to analyze oil degradation. The data was recorded for two years for two turbines. Then filter lifetime can be predicted by processing the recorded data with statistical and semantic method. The combination of statistical and semantic method make the technique hybrid.

Michael Wilkinson et al. (2007) [16] develop a electomechanical test rig for assessment that which sensor and fault detection algorithm should be used in a condition monitoring system for operational wind turbines. The test rig has been driven at variable speed to investigate the behavior of wind turbine. A number of fault detection algorithms have been tested on each sensor signal.

Edwin Wiggelinkhuizen et al. (2007) [17] set up a wind farm of five turbines and several condition monitoring systems has been installed. Traditional measurement systems are also used. A algorithm has been developed which can be integrated with a SCADA system.

German Wind energy Association (2007) [18] highlights the objective and condition monitoring intervals according to the wind turbine size in megawatt. They highlight the technical experts qualification required for CM plan, inspection requirements, maintenance requirements and technical control system requirements.

Michael R. Wilkinson (2007) [19] constructed 30 kW test rig which have the same feature as wind turbine drive train, for signal processing technique necessary for variable speeds and high torque variation application. The faults are detected by investigating various approaches of condition monitoring on this test rig, and measuring torque, speed and shaft displacement and gearbox vibrations.

R. Andrew Swartz et al. (2008) [20] deployed wireless sensor technology on two wind turbines to construct better models of wind turbine dynamic behavior and response to loading.

Scott J. Johnson et al.(2008) [21] presented a report in which they introduces a number of active techniques which can be used for control of wind turbine blades. They apply active flow control (AFC) to wind turbine performance and loads. A special focus was given on actuators and devices and flow phenomena caused by each device.

Mike Woebbeking (2008) [22] performed various kind of inspections at turbines. The inspection include periodic monitoring, operation and maintenance surveillance, inspection after commissioning of wind turbine etc. The results shows that 26% of defects and damages are due to gearbox, 17% from generator and 13% from drive train.

Asif Saeed (2008) [23] implemented various conventional and latest techniques of condition monitoring including signal processing methods for vibration analyses for early fault detection. As a result of the study, infrared thermography is applied as an online condition monitoring for wind system as a retrofit design to increase performance of early detection system.

William A. Vachon (2008) [24] presented a work which focuses on joint wind project involving IMLD and IpsWich school District (ISD). They install a single MW scale wind turbine generator and the output of the generator is shared in proportion according to funds provided by each party, and value of power delivered to each party reflect the projected time of use of costs. Thus goal of the study was to project the economics of the project.

E Lie-Ahmar et al (2008) [25] presented a work which investigate specific transient techniques suitable for electrical and mechanical failures in an induction generator based wind turbine. An experimental set up of 1.1kW has been constructed and investigations shows that proposed technique can diagnose failure under transient condition.

Cattin Rene et al. (2009) [26] concludes some results from turbines working in ice regions. They revealed that in cloud conditions the air temperature can be used as an indicator for detecting icing conditions. They point out that there is no ice detector in market which can measure icing reliably.

The results of Enrcon E-40 turbine shows that the ice detection via power curve can be a better method except for light icing and in case of low wind speed. They point out that it is not possible to melt ice during one heating cycle specially at leading edge of blades thus heat transfer to leading edge should be optimized.

Yassine Amirat et al. (2009) [27] discussed different types of faults, Their generated signature and their diagnostic scheme by keeping in mind the need for future research.

T. Barszczet et al. (2009) [28] states that there is lack of sufficient data to perform training of method, thus some new states should have created, when there is data different from all known states. Thus they apply Neural Network approach because Neural is a proper tool for classification of operational states in wind turbine and is also capable to recognize new states.

R.F. Mesquita et al. (2010) [29] apply the Neural network to analyze all the wind turbine information to identify possible future failure, based on past data of turbine. They show that neural network is a valid tool to make an early detection of failure in some wind turbine equipments.

Emilio Miguelanez et al. (2010) [30] presents the role of SeeByte's RECOVERY system within the wind industry, specially focus on offshore turbines. Systems of today gives false alarms most of the time which results in incorrect diagnosis and unnecessary intervention and important warnings are ignored. A RECOVERY system has been developed to guide the fault detection process and better automate knowledge discovery to improve diagnostics. The diagnostics concept is represented on the basis of system observation design pattern. This holistic system improve the diagnostic correctness by taking care of events and sensors values for complete turbine system. Thus it reduces the no-fault-found situations.

Bincheng Jiang (2010) [31] analyze the dynamic performance of drive train in wind power station and dynamic behavior of gearbox under normal and transient load conditions has been studied to investigate the reasons of drive train misalignment in future work. A 1-D torsional multibody dynamic model of the drive train taking into account the effect of aerodynamic force and excitation has been developed.

Wenxian Yang et al. (2010) [32] presented a CM technique in which generator output power develop a fault detection signal. A algorithm is used which uses continuous wavelet transform. Adaptive filters are used to track the energy in prescribed time-varying fault-related frequency bands in power signals. The generator control the central frequency and band width is related with speed fluctuations. Using this technique faults can be detected with low calculations time.

Yassine Amirat et al. (2010) [33] proposed a new fault detector which is based on amplitude demodulation of the three phase stator. They proves by simulation that this low complexity method can be well applied for stationary and non stationary behavior.

Milos Milovancevic (2010) [34] states that applied condition monitoring techniques on sub system levels produces useful information about wind turbine. By using advanced methods of signal analyses, significant changes in turbine behavior can detected at an early stages. They develop a approach which is based on general turbine parameters. Due to global nature of information specific diagnostic is difficult to achieve. Thus they develop a system for wind generator transmission gear vibration monitoring. They proposed that wind turbine systems are complex to monitor and there are very small margins for investments and number of systems is high hence adaptation should not only focused on dynamic load behavior but also on streamlining the system and integration.

Joon Young Park et al. (2010) [35] develop a simulator composed of blades, a step up gearbox and a generator. This simulator replaced the conventional simulator which consist of a motor and was not suitable for effective condition monitoring algorithm. They developed the condition monitoring system and also the procedure for designing the simulator.

Eunshin Byon et al. (2010) [36] present a work which shows the effect of dynamic weather conditions on feasibility of maintenance. That state that weather conditions makes the modeling and maintenance strategy season dependent. They formulate a model based on Markov decision process by accounting heterogeneous parameters and solve the model by backward programming method. They highlight the benefits of resulting strategy through a case study by collecting data from wind industry. The case study results shows that a optimal policy can be adapted to operating conditions, choosing the most effective action.

Richard Dupuis (2010) [37] explains that how bearing and gear rolling elements fails by surface fatigue mode and also study the characteristics of debris produced by failure mode. Their work present that how the accumulated debris damage limit can be counted on the basis of gear geometry. They develop an effective PHM technique by presenting actual data obtained from seeded fault bearing and gear test.

Zhi Gang Tian et al. (2010) [38] develop a optimal CBM defined by two failure probability thresholds values at wind turbine level. The CBM decisions can be made by calculating failure probability values on the basis of condition monitoring and prognostic data. The cost of CBM technology is evaluated by simulation.

F.D. Coninck et al. (2010) [39] constructed a back to back gearbox setup which is one of the largest in world. The complexity of dynamics was tackled by the concept of load cases. Each load case represent different turbine behavior. A control architecture was developed to handle the complex interactions between mechanical dynamics and electrical controller of test rig. The test rig is fit for experimental validation of dynamic load situation models.

Bodil Anjar et al. (2011) [40] conducted a feasibility study and they investigate the possibilities of using thermal condition monitoring of the systems and components in wind turbines. They conclude that thermography is suitable for monitoring electrical systems, transformers and also for fire detection and fire extinguishing. The IR cameras can be mounted on a pan tilt unit for continuous monitoring. They show that as the size of wind power plant increases the cost for downtime and repair also increases.

Shuangwen Sheng (2011) [41] present a study work which focuses on results obtained by various CM techniques from a damaged Gearbox Reliability Collaborative (GRC) test gearbox. The study shows the capabilities and limitations of each technique. The results from a test gear box under healthy condition are compared with damaged gearbox. A fieldtest of one GRC gearbox shows that damaged gearbox experienced two unexpected oil losses which damage its internal components. The damaged gearbox is reset by using different CM techniques which help in evaluating the different CM techniques.

Pratesh Jayaswal et al. (2011) [42] present a work in which they acquired the vibration signals of bearings and analyzed them with the help of vibration analyses techniques. In present work they detect the earlier fault in bearing using vibration monitoring. By study the FFT spectrum of bearing vibration signal they access the condition of bearing.

Peng Guo et al. (2011) [43] proposed a new technique Autoassociative Kernel Regression (AAKR) which is used to construct the normal behavior model of gearbox temperature. The measurement temperature become significant, when residual between AAKR estimates on incipient failure of gearbox. To detect the changes of the residual mean value and standard deviation in timely manner a moving window statistical method is used. As one of these parameters exceeds the predefined value the incipient failure flagged.

Secil Vorbak Nese et al. (2011) [44] constructed a model of three blades horizontal axis turbine and fault due to possible blade deformation was studied. By applying Continuous Wavelet Transform (CWT) approach a comparison is done between generator rotor speed and torque for healthy and damaged blades.

Suratsavadee Koonlaboon Korkua et al. (2011) [45] develop a Zig Bee based wireless sensor network for health monitoring of induction machines. The proposed technique is like a control network which integrates sensors and embedded computer, wireless communication and intelligent processing technology. The proposed technology consumes low power, having low cost and short time delay characteristics. The technique is used with suitably modified algorithm for extracting the information for induction machine diagnostic.

Dariusz BRODA et al. (2011) [46] states that vibration of wind turbine is greatly affected by wind. They discuss the seasonal diurnal vibrations with the help of statics of wind and vibrations. Variability of wind and vibrations are compared with the help of mean/std ratio. The results obtained help in determining operational states of wind turbine.

Joon-Young Park et al. (2011) [47] present a work in which they develop a condition monitoring system for three different kind of SCADA system of three different turbines from different manufacturer. Thus their work include the designing of condition monitoring system and design of its control function.

Douglas Adams (2011) [48] presented a work in which they perform the structural health monitoring of Micon 65/13 horizontal axis wind turbine. It is observed that vertical wind shear and turbulent wind load to different modal contributions in operational response of the turbine and they conclude that sensitivity of operational data to change depends upon the wind loads. A modal criterion was used to analyze corresponding changes in modal deflections.

Ivo Houtzager (2011) [49] addressed two research goals one deal with the data driven modeling methods using system identification and other deal with repetitive controller to reject periodic disturbances. In first method the recursive identification is performed via the subsequent solution of only three linear problems and they are solved by recursive least square. They use Tikhonov regularization to overcome possible numerical problems in practice. The real time implementation and ability to multi input and output systems with closed loop make this approach best suitable for unstable dynamics estimation.

Radoslaw Zimroz et al. (2011) [50] proposed the use of advanced signal processing techniques for measuring instantaneous shaft speed recovery from vibration signals generated.

Peng Gua (2012) [51] used the history data of Supervisory Control and Data Acquisition (SCADA) system and analyzed this data for detecting the failure of turbine generator bearing. A new condition monitoring method based on Nonlinear State Estimate Technique (NSET) is proposed which is used to construct the normal behavior model of generator bearing temperature. When the generator bearing has an incipient failure the residual between NSET model estimates and measured generator bearing temperature will become insignificant and when residual exceeds the thresholds, an incipient failure is flagged.

Wenxian Yang et al. (2012) [52] proposed that reliability centered maintenance is best for offshore wind turbines which include preventive and predictive maintenance techniques enabling wind turbine to achieve high availability and low cost of energy. They present the wind industry with a detailed analyses of the current challenges with existing wind turbine condition monitoring technology.

Simon Gill et al. (2012)[53] used the operational data from wind turbine to estimate bivariate probability distribution functions representing the power curves of existing turbines. Hence deviations from expected behavior can be detected. They proposed application of empirical copulas to reduce the complexity between active power and wind speed which was either impossible to approximate by any parameterized distribution.

Bill Chun et al. (2012) [54] addressed that cost of manufacturing, logistics, installation, grid control and maintenance of offshore wind turbine is high. They apply Prognostics and system Health Management (PHM) to enhance the cost effectiveness of the maintenance strategy.

Wenxian Yang et al.(2012) [55] developed a new online, load independent, condition monitoring technique based on concept of information entropy. An entropy based condition monitoring strategy has been developed and verified by applying it to vibration and electrical signals from a specially designed wind turbine condition monitoring test rig and hence they proposed that this technique is reliable for detecting mechanical and electrical faults in wind turbines.

Y. Wang et al. (2012) [56] uses a Nonlinear State Estimation Technique (NSET) to model a healthy wind turbine gearbox using stored historical data. A model is constructed which have interrelationship between model input and output parameters and covers as much turbine operational range as possible and model is applied to access the operational data. Welch's test together with suitable time series filtering is used in the algorithm so that faults can be detected before they develop into catastrophic failure.

Dr. Wei Qiao (2012) [57] reduces the complexity of sensors which are difficult to access during wind turbine operation. A nonintrusive lower cost and more reliable technology is developed. This technology uses only the phase current signals to measured from generator stator terminals for condition monitoring of wind turbines. The Proposed technology eliminate the use of sensors or data acquisition system.

Zijun Zhang (2012) [58] use three models for detecting abnormalities of wind turbine vibrations reflected in time domain. Supervisory Control and Data Acquisition (SCADA) data collected from various turbines is used to develop models. The vibrations of wind turbine is characterized on the basis of drive train and tower acceleration. An unsupervised data mining algorithm, the k mean clustering algorithm was applied to develop the first monitoring model and other two are developed by using the concept of control chart for detecting abnormal values of drive train and tower acceleration.

Shane Butler et al. (2012) [59] develop a methodology to estimate the Remaining Useful life (RUL) of the main bearing of commercial wind turbine. A residual model was developed to indicate a faulty behavior, Which produce a signal on post processing for extrapolation using particle filters. The RUL is then specified in term of probability distribution which narrows as the failure point is approached.

Deepak Kumar et al. (2012) [60] proposed the wavelet transform technique for the monitoring and fault diagnosis of wind turbine to eliminate the disadvantages of conventional spectral techniques in processing instantaneous turbine signals. The technique is applied to generators which are directly coupled to the turbine. The technique diagnosis the imbalance of rotor and heralding. Eric Bechoefer et al. (2012) [61] installed a condition monitoring system on a utility scale wind turbine and. The system produces a number of unexpected results. The installation allowed testing of a microelectromechanical system based sensor technology and vibration data & RPM data was analyzed. They observed that ability to easy measure changes in main rotor RPM as a result of tower shadow and wind shear phenomenology also facilitate the detection of icing on blade pitch error.

K. Smarsly et al. (2012) [62] Developed an autonomous software based on multi-agent technology to detect any malfunctioning in the system. The software is modularly integrated into the monitoring system to monitor the installed sensor. A e-mail notification were automatically composed and immediately send to the responsible personnel. As a result appropriate actions were undertaken in time.

Anoop Prakash verma (2012) [63] presents the wind turbine performance monitoring using historical wind turbine data. A model was constructed using SCADA operational data and fault logs. Two research directions were proposed first is identification and production of critical turbine fault and second is to monitor overall wind farm. The performance of overall wind farm can be accessed daily, weekly or monthly basis.

Lain Dinwoodie et al. (2012) [64] applies an auto regressive (AR) climate modeling approach to simulate both wind and wave time series coupled with Markov chain Monte Carlo (MCMC) based failure simulation. The AR approach produces rapidly a synthetic time series on the basis of site data available. Failures are simulated on the basis of failure rates and associated time to repair based on simulated weather climate. They investigate that how turbine size influence the breakdown of operational costs. The modeling methodology has been developed to investigate novel asset management techniques and to identify and quantify the sensitivity of overall cost to key operational parameter.

Takeshi Ishihara (2012) [65] proposed a concept of physical model based condition monitoring (PCM) including system identification and dynamic response analyses using advanced wind field model. The model is introduced to cost effective and reliable condition monitoring. Damping effects of movable parts are identified and then evaluated. Various parameters of model are determined and difference of damping in fore and aft and side by side are expressed.

Schlechtingen, Meik et al (2012) [66] in their approach employed Neuro-Fuzy interface system (ANFIS) models in training phase. Then trained models applied to product predict the target signals in application phase eg. Temperature, pressure, currents etc. The normal or abnormal behavior of component can be indicated by prediction error with respect to learned behavior. This method is applied to 18 onshore wind turbines of 2MW and results shows that proposed method is well suited to closely monitor a large variety of signals. The accuracy of developed model is high hence even a small behavior changes can be detected.

Walter Bartelmus (2012) [67] present a new way of diagnostic which is based on object and operation factor oriented analyses. The data is presented in the term of susceptibility characteristics. The system shows two types of susceptibility. With increase in load mean value of generated vibration given by acceleration signal increases, and change in object condition, create a parallel shift of susceptibility characteristics.

Robert B. Randall et al. (2012) [68] presented a work in which a number of ways for compensating for speed and load variations on basis of obtained signals from study of natural occurring faults in wind turbine transmission were discussed. The gearbox was mounted on a test rig and a “pseudo-encoder” signal is extracted from a vibration signal.

Pavle Boskoski and Dani Juricic (2012) [69] propose an approach for gear fault prognosis in non stationary and unknown operating conditions. In this approach the evolution of statistical complexity of the generated vibration envelop are monitored. The wavelet coefficients are calculated from generated vibrations and statistical complexity is then obtained from wavelet coefficients. The approach estimates the remaining useful life of component without any information about operating conditions and its physical characteristics.

Mohamed Elforjani and David Mba (2012) [70] presented a work to detect natural defect initiation and crack propagation in rolling element bearing. They construct a test rig to allow accelerated natural degradation of bearing race and concluded that AE is able to detect sub surface initiation and crack propagation.

Ridha Ziani et al. (2012) [71] presented a work in which they compare the performance of bearing fault detection by using Artificial Neural Network (ANN) and Genetic algorithm(GA). The time domain signals from normal and defective gear boxes are extracted and used as input to ANN. The system features are selected on the basis of genetic algorithm and linear Discriminant analyses (LDA) is used as evolution function.

Hedi Hamdi et al. (2012) [72] presented a work to determine the influence of the gyroscopic couple on dynamic behavior of blades made of glass fiber reinforced (GRP).

Yassine Driss et al. (2012) [73] present a wind turbine with a helical three stage gear system having twenty eight degree of freedom. The aerodynamic forces are considered constant and excitation of the model is induced by periodic variation of mass stiffness. Then dynamic response is calculated by integration method. Finally variation of aerodynamic force is introduced in model and their effect on gear system behavior is studied.

Jin Zhang et al. (2012) [74] state that impulses in vibration signals and their spectral features are the key indicators for diagnosing gear damages. They proposed a new method time wavelet energy spectrum for extracting characteristic frequency of faulty gears. The experimental results shows that this method can highlight impulses and is very effective for extracting repeating frequency of periodic impulses and it can even extract the weaker fault feature of gear tooth wear.

Mohamed Boufenar et al. (2012) [75] presented a work in which they study, compare and modify the time frequency representation techniques such as Wigner Ville Distribution(WVD), Short Time Fourier Transformation (STFT) and wavelets to analyses non stationary phenomena.

Ilyes Khelf et al. (2012) [76] proposed a diagnostic method of rotating machinery using vibration signature and residual basis function classifier. Wavelet Decomposition method is used to process the recorded signals and indicators are extracted both in temporal and frequency domain. To improve the performance of diagnostic two techniques reduce of indicators space were combined. The method was tested on real signature at various operating condition on a test rig and results shows that choice of indicators closely affect the diagnosis performance.

Michael G. Lipsett (2012) [77] point out that an effective condition monitoring system depends on good observability of effects of a fault. Thus a simple framework has been described for incorporating damage accumulation into lumped parameter system models.

Ryszard Makowski et al. (2012) [78] proposed a adaptive algorithm for vibration signal modeling to enhance local changes of signal statics. The approach is based on the normalized exact least square time variant lattice filter (Adaptive Schur Filter). This filter have a fast parameters tracking capability, fast start up and excellent convergence behavior. Thus this method is well adapted for diagnostics of gear box working in time varying load and speed conditions.

Radoslow Zimzoz et al. (2012) [79] apply statistical feature processing instead of simply comparing value with threshold. It has been observed that data behavior and good-bad separation of data is different for different load conditions. It proves that recognition efficiency is better for decomposed data than for all data taken together.

Michael Wilkinson et al. (2013) [80] proposed that operational costs get greatly reduced by monitoring the condition of major components in the drive train. They conduct the validation study on this method using five wind farms and conclude that a good detection accuracy and high detection rate is possible.

Dr. Shaik Nafeez Umar et al. (2013) [81] apply acoustic emission technique for condition monitoring of wind turbine and they conclude that AE technique can be successfully applied for condition monitoring of low speed rotating components. They observed that technique is able to detect very small energy release rates due to incipient failure at starting stage.

Schlechtingen, Meik (2013) [82] present a system for wind turbine condition monitoring by using adaptive Neuro-Fuzy interference systems (ANFIS). To fulfill the purpose a normal behavior model for common SCADA are developed to detect abnormal signals.

Van Horenbeek, Adriaan et al. (2013) [83] state that it is difficult to implement condition monitoring system due to uncertain parameters. They take into account the performance of the condition monitoring system itself which had been neglected in most of available literature. The modeling is done on the base of P-F curve for for different failure modes and then implemented on turbine gearbox. The case study proves that condition monitoring system is beneficial as compare to other maintenance strategies and benefit depends directly on performance of CBM.

A.Augustin Rajasekar (2013) [84] presented a work to investigates online condition monitoring based on voltages and currents for diagnosis of mechanical wind turbine brake. They conclude that the application of online condition monitoring systems can optimize maintenance scheduling but by evolution of condition based maintenance procedure rather than corrective maintenance and minimizes the rest of catastrophic failures.

Tommi Karkkainen et al. (2013) [85] point out that there is no generally accepted widely deployed condition monitoring method for power converters. Thus in this study they investigate the benefit and desirability of condition monitoring for electronic converter.

VIII. Summary of Literature Survey

Table 8.1: Summary of developments in condition monitoring techniques based on literature survey

Refno.	Author, Year	Investigated Problem Type
1	Palle Christensen et al.(2001)	Automatic supervision and control of wind turbines
2	T. Holroyd (2001)	Defect of varying size on outer races of bearings.
3	N.Jamludin et al. (2001)	Stress wave analyses to detect early stages damages
4	Shjn Dander (2002)	Time domain model based fault detection
5	T.W. Verbruggen (2003)	Develop inventory of available condition monitoring techniques
6	L. Mihet-Popa et al. (2003)	Steady state technique for detection of interturn stator faults
7	L.W.M.M. Rademakers et al. (2004)	Condition monitoring of fibers blades
8	Giurgiutiu,V (2005)	Fault detection method based on ultrasonic rely
9	Douglas H. (2005)	Fault detection in Doubly Fed induction generator
10	Christopher A. Walfard (2006)	Reliability of wind power generation
11	C. Walfard (2006)	Cost estimation of failure of wind turbine
12	R.W. Hyers et al. (2006)	Comparison of CM techniques of turbine and helicopter gearbox
13	Jesse A. Andrawus et al. (2007)	Detection of wind turbine faults using RCM
14	David Mc Millan et al. (2007)	Measurement of benefits of CM quantitatively
15	Ayetullah Gunel et al. (2007)	Fluid condition monitoring technique
16	Michael Wilkinson et al. (2007)	Selection of sensors and algorithm
17	Edwin Wiggelinkhuizen et al. (2007)	Algorithm based on SCADA
18	German wind energy association (2007)	Requirement of a CM plan
19	Michael R. Wilkinson (2007)	Signal Processing technique
20	R.Andrew Swaetz et al. (2008)	Dynamic behavior and loading of wind turbine
21	Scott. J. Johnson et al. (2008)	Active flow control
22	Mike Woebbeking (2008)	Percentages of various type of damages responsible for failure
23	Asif Saeed (2008)	Fault detection by signal processing techniques
24	William A. Vachon (2008)	Project Economics
25	E Lie-Ahmar et al. (2009)	Transient Techniques
26	Cattin Rene et al. (2009)	CM techniques for wind turbines in icy regions
27	Yassine Amirat et al. (2009)	Faults and their signatures
28	T. Barszczet et al. (2009)	Fault detection by Neural Network approach
29	R.F. Mesquita et al. (2010)	Fault detection by Neural Network approach
30	Emilio Miguelanez et al. (2010)	Role of See Byte's Recovery system in wind industry
31	Bincheng Jiang (2010)	Dynamics behavior of gear boxes in transient conditions for fault detection
32	Wenxian Yang et al. (2010)	Continuous Wavelet Transform
33	Yassine Amirat et al. (2010)	Fault detection based on amplitude demodulation of three phase generator
34	Milos Milovancevic (2010)	Dynamic load behavior and streamlining
35	Joon Young et al. (2010)	Designing of a new simulator
36	Eunshin Byon et al. (2010)	Effect of weather conditions on feasibility of maintenance
37	Richard Dupuis (2010)	Characteristics of debris produced after failure mode
38	Zhigang Tian et al. (2010)	CBM decisions made by calculating failure probabilities
39	F.D. coninck et al. (2010)	Reproduction of dynamic load for wind turbine gearbox
40	Bodil Anjar (et al.2011)	Feasibility of thermal condition monitoring
41	Shuangwen Sheng (2011)	Condition monitoring of wind turbine gearbox

42	Pratesh Jayashwal et al.(2011)	Fault detection in bearings
43	Peng Guo (2011)	Fault detection in gearboxes using AAKR
44	Secil Vorbal Nese et al. (2011)	Faults due to blade deformation
45	Suratsavadee Koonlaboon Korkua et al. (2011)	Monitoring of induction machines
46	Dariusz Broda et al. (2011)	Varying operational conditions in wind turbines
47	Joon-Young Park et al. (2011)	Development of CM system with control functions
48	Douglas Adams (2011)	Structural health monitoring of horizontal axis wind turbine
49	Ivo Houtzager (2011)	Data driven control for wind turbines
50	Radoslaw Zimroz et al. (2011)	Fault detection in gearboxes using signal processing
51	Peng Gua (2012)	Failure detection of turbine generator bearing
52	Wenxian Yang et al. (2012)	Challenges with existing wind turbine condition monitoring techniques
53	Simon Gill et al. (2012)	Fault detection on the basis of power curves
54	Bill Chun et al. (2012)	Failures and fault prognostics methods
55	Wenxian Yang et al. (2012)	Condition monitoring on basis of information entropy
56	Y. Wang et al. (2012)	Gearbox fault detection by NSET technique
57	Dr. Wei. Qiao (2012)	Current based online condition monitoring
58	Zijun Zhang (2012)	Monitoring of wind turbine vibrations using SCADA data
59	Shane Butler et al. (20120	Bearing life failure and life estimation
60	Deepak kumar et al. (2012)	Condition monitoring of utility scale wind turbine
61	Eric Bechoefer et al. (2012)	Testing of microelectromechanical system based on sensor and RPM data
62	K Smarsly et al. (2012)	Monitoring of wind turbine with autonomous software
63	Anoop Prakash Verma(2012)	Wind turbine performance monitoring using SCADA system
64	Lain Dinwoodie et al. (2012)	Sensitivity of wind turbine to operational parameters
65	Takeshi Ishihara (2012)	Fault detection by dynamic response of wind turbine
66	Schlechtengen, Meik et al. (2012)	Fault detection by Neuro-Fuzy interference system (ANFIS)
67	Walter Bartelmus (2012)	Diagnostic based on object and operation factor
68	Robert B. Randall et al. (2012)	Fault detection in wind turbine Gearbox
69	Pavle Boskoski et al. (2012)	Gear fault detection in non stationary and unknown operating conditions
70	Mohamed Elforjani et al. (2012)	Natural fault detection in rolling element bearing
71	Ridha Ziani et al. (2012)	Fault detection in bearing using Artificial Neuro Network
72	Hedi Hamdi et al (2012)	Effect of gyroscopic couple on dynamic behavior of blades
73	Yassine Driss et al. (2012)	Dynamic behavior of aerodynamic turbines
74	Jin Zhang et al. (2012)	Gearbox fault analyses
75	Mohamed Boifenar et al. (2012)	Study, compare and modification of time frequency techniques
76	Ilyes Khelf et al (2012)	Diagnostic of rotating machinery using vibration signature
77	Michael G. Lipsett (2012)	Observability requirement for condition monitoring
78	Ryszard Makowski et al. (2012)	Local damage detection in gearboxes
79	Radoslow Zimzoz et al. (2012)	Turbine generator bearing diagnostics
80	Michael Wilkinson et al. (2013)	Comparison of methods for wind turbine CM with SCADA
81	Dr. Shaik Nafeez Umar et al. (2013)	Acoustic emission condition monitoring
82	Schlechtingen, Meik (2013)	Fault detection by Artificial Neuro-Fuzy Interference System
83	Van Horenbeek et al. (2013)	Fault detection in wind turbine gearbox
84	A.Augustin Rajasekar (2013)	Retrofit the mechanical braking system using CM system
85	Tommy Karkkainen et al (2013)	Necessity of CM in electronic converter

IX. Conclusions

This paper provides an overview of RP Technology in brief and emphasizes on their ability to shorten the product design and development process and detail of few important processes is given. The RP technologies provide the freeform fabrication of the complex geometry directly from their CAD models automatically.

The future looks very promising for rapid prototyping. The benefits for most applications far outweigh the disadvantages especially when they are used in the correct situation. The price and size are rapidly falling to the point where they will soon be commonplace in any manufacturing company.

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