

Condition Monitoring of Wind Turbines: A Review

Sachin Sharma¹

¹ Green Hill Engineering College Kumarhutti Solan (H.P.T.U.)

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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.

Index terms— wind energy, condition monitoring.

1 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. On the basis of data acquisition and periodicity analyses machine protection system can be of following 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 b. ONLINE system: The permanently installed system for 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 device and periodically 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.

Figure 1.2 : Different approaches to condition based maintenance for different equipment in the plan 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

46 and data transfer is cheap. By introducing a high speed computer network into vibration monitoring system,
47 vibration signals can be transferred into a specific database. Using this data maintenance managers and vibration
48 specialists have a real time insight into a machine's condition. Web based condition monitoring can be applied to
49 both OFFLINE and ONLINE monitoring system. However it is generally applied to ONLINE system and in case
50 of OFFLINE system means only remote database and vibrations specialists while the presence of maintenance
51 personnel on site is still required for purpose of vibration data collection.

52 CBM is performed to serve the following purposes:

53 ? To identify the fault in the monitored object.

54 ? To identify nature of fault.

55 ? To determine the time up to which machine can serve without interruption before breakdown. ? To
56 determine the degrading components.

57 ? The core objectives of condition based maintenance are: ? To take necessary action before breakdown.

58 ? To reduce the maintenance overhead costs.

59 ? To perform maintenance when required.

60 2 ?

61 To reduce number of breakdowns and failure frequency rate.

62 3 II. How to Start Condition based Maintenance

63 One of the most attractive aspect of CBM is the fact that it can be implemented in a relatively inexpensive, step
64 by step approach. Because condition based maintenance is based on equipment oriented concepts of predictive
65 maintenance, it can be applied gradually one system a time. a) Phase 1 i. Data collection and storage procedure
66 Maintenance data and its uses creates the main key differences between the classical and modern maintenance
67 methods. In past, a little attention was paid for the comparison and trending and the data was collected
68 from maintenance results from any given interval which had been filed by reviewing. Trending and statistical
69 analyses are the fundamental building blocks of CBM. By comparing data absolute values and data deviations via
70 statistical analyses provide information never before available. Thus a statistically relevant data base is required.
71 There are a lot of maintenance management software available which have same basic purpose and design are
72 similar from one manufacturer to other. Fundamental equipment information is stored in a detailed manner.
73 Information such as size, date of purchase, ratings, cost, maintenance cycle etc. are stored. Many power system
74 operators have kept good paper records over the years. These paper records may be converted into computerized
75 database which is time consuming but simple.

76 4 Objectives of CBM

77 Following steps are involved in condition based maintenance:

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

82 5 iii. Equipment Database

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

85 6 iv. Preliminary budget and plan

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

88 7 IV.

89 8 Condition Monitoring of Wind Turbines

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

100 the industry [88,89] and its most benefits are used in offshore wind farms [90]. For wind turbines this type of
101 monitoring is applicable for monitoring the wheels and bearings of the gearbox, bearings of the generator and
102 the main bearing. Signal analysis requires specialised knowledge. Suppliers of the system offer mostly complete
103 systems which includes signal analysis and diagnostics. The monitoring itself is also often executed by specialised
104 suppliers who also perform the maintenance of the components. The costs are compensated by reduction of
105 production losses. Application of vibration monitoring techniques and working methods for wind turbines differ
106 from other applications with respect to: ? The dynamic load characteristics and low rotational speeds In other
107 applications, loads and speed are often constant during longer periods, which simplifies the signal analysis. For
108 more dynamic applications, like wind turbines, the experience is very limited. ? The high investment costs in
109 relation to costs of production losses. The investments in conditions monitoring equipment is normally covered by
110 reduced production losses. For wind turbines, especially for land applications, the production losses are relatively
111 low. So the investment costs should for a important part be paid back by reduction of maintenance cost and
112 reduced costs of increased damage.

113 9 V. Condition Monitoring Techniques

114 10 b) Oil Analysis

115 Oil analysis may have two purposes:

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

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

124 11 c) Thermography

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

131 12 d) Physical condition of materials

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

135 13 e) Strain Measurement

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

142 14 f) Acoustic Monitoring

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

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

149 15 g) Electrical Effects

150 For monitoring electrical machines MCSA (Machine Current Analysis) is used to detect unusual phenomena. For
151 accumulators the impedance can be measured to establish the condition and capacity. For medium and high
152 voltage grids, a number of techniques are available: ? Discharge measurements ? Velocity measurements for
153 switches ? Contact force measurements for switches ? Oil analysis for transformers For cabling isolation faults

154 can be detected. These types of inspection measurements do not directly influence the operation of the wind
155 turbines.

156 16 h) Process Parameters

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

162 17 i) Performance Monitoring

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

167 18 VI. Possible Applications of Condition Monitoring

168 19 Literature Review

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

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

175 N. Jamludin et al. (2001) [3] present a work in which they apply the stress waves analyses to detect early
176 stages damages of bearing at a very low speed i.e. 1.12r/min. Shjn Dander (2002) [4] presented a work in which
177 they access the use of time domain model based fault detection and identification (FDI) method for application
178 to a horizontal axis wind turbine (HAWT) that uses pitch to vane control. They use two approaches, the system
179 identification approach and observer based approach using the kalman filter. They construct a horizontal axis
180 wind turbine model and use the simulation to test various approaches. Two algorithms based on kalman filter
181 are presented which provide a reliable estimate of the wind speed by including it in an augmented system state.

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

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

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

191 Giurgiutiu, V & Cuc, A. (2005) [8] presented a damage detection method which was based on ultrasonic rely
192 due to propagation and reflection of elastic waves within the material. They identify local damages and flaws via
193 blade field disturbances. They propose the use of piezoelectric transducer in place of conventional non destructive
194 transducer because piezoelectric transducer can act both transmitter and receiver of ultrasonic waves. Douglas
195 H. (2005) [9] presented a work in which a steady state technique has been applied e.g. Motor Current Signature
196 Analyses (MCSA) and Extended Park's Vector Approach (EPVA) and a new technique which was combination
197 of EPVA and discrete wavelet transform and statics to detect the turn faults in doubly fed induction generators
198 (DFIG). The proposed technique shows that steady state technique is not effective when DFIG's operate under
199 transient condition but stator turn faults can be detected under transient conditions.

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

203 C. Walfard, D. Robert (2006) [11] present a work in which they conduct a cost benefit analyses and estimates
204 that cost liability for failure of wind turbine after four to five years is \$75,000 to \$ 2,25,000 per event for megawatt
205 scale turbine. R.W. Hyers et al. (2006) [12] compare the condition monitoring in wind turbine with monitoring
206 and prognosis in helicopter gearboxes. They evaluate the state of art of electronic control and power electronics
207 and compare with state of art in aerospace.

208 Jesse A. Andrawus et al. (2006) [13] apply the RCM approach to horizontal axis wind turbine to detect
209 various failure modes and their causes and effects on system operation. The failure consequences are estimated in
210 term of financial terms by evaluation. Over the whole life cycle of wind turbine the CBM activities are identified
211 and assessed to maximize the return on investment in wind farms. ??avid [15] present a new technique i.e. fluid

212 condition monitoring system in which temperature of oil filter and cooling subsystems are monitored with various
213 sensors. The other parameters such as absolute pressure drop across the filter, dielectric constant and viscosity
214 are also monitored to analyze oil degradation. The data was recorded for two years for two turbines. Then filter
215 lifetime can be predicted by processing the recorded data with statistical and semantic method. The combination
216 of statistical and semantic method make the technique hybrid.

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

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

224 German Wind energy Association (2007) [18] highlights the objective and condition monitoring () [20] deployed
225 wireless sensor technology on two wind turbines to construct better models of wind turbine dynamic behavior
226 and response to loading.

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

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

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

239 E Lie-Ahmar et al (2008) [25] presented a work which investigate specific transient techniques suitable for
240 electrical and mechanical failures in an induction generator based wind turbine. An experimental set up of
241 1.1kW has been constructed and investigations shows that proposed technique can diagnose failure under transient
242 condition.

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

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

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

251 T. (2009) [28] states that there is lack of sufficient data to perform training of method, thus
252 some new states should have created, when there is data different from all known states. Thus they apply Neural
253 Network approach because Neural is a proper tool for classification of operational states in wind turbine and is
254 also capable to recognize new states. R.F. Mesquita et al. (2010) [29] apply the Neural network to analyze
255 all the wind turbine information to identify possible future failure, based on past data of turbine. They show
256 that neural network is a valid tool to make an early detection of failure in some wind turbine equipments.

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

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

272 Joon Young Park et al. (2010) [35] develop a simulator composed of blades, a step up gearbox and a generator.
273 This simulator replaced the conventional simulator which consist of a motor and was not suitable for effective

274 condition monitoring algorithm. They developed the condition monitoring system and also the procedure for
275 designing the simulator.

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

282 Richard Dupuis (2010) [37] explains that how bearing and gear rolling elements fails by surface fatigue
283 mode and also study the characteristics of debris produced by failure mode. Their work present that how the
284 accumulated debris damage limit can be counted on the basis of gear geometry. Ivo Houtzager (2011) [49]
285 addressed two research goals one deal with the data driven modeling methods using system identification and
286 other deal with repetitive controller to reject periodic disturbances. In first method the recursive identification
287 is performed via the subsequent solution of only three linear problems and they are solved by recursive least
288 square. They use Tikhonov regularization to overcome possible numerical problems in practice. The real time
289 implementation and ability to multi input and output systems with closed loop make this approach best suitable
290 for unstable dynamics estimation.

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

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

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

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

307 Bill Zijun Zhang (2012) [58] use three models for detecting abnormalities of wind turbine vibrations reflected
308 in time domain. Supervisory Control and Data Acquisition (SCADA) data collected from various turbines is
309 used to develop models. The vibrations of wind turbine is characterized on the basis of drive train and tower
310 acceleration. An unsupervised data mining algorithm, the k mean clustering algorithm was applied [2012] [61]
311 installed a condition monitoring system on a utility scale wind turbine and. The system produces a number of
312 unexpected results. The installation allowed testing of a microelectromechanical system based sensor technology
313 and vibration data & RPM data was analyzed. They observed that ability to easy measure changes in main rotor
314 RPM as a result of tower shadow and wind shear phenomenology also facilitate the detection of icing on blade
315 pitch error. K. Smarsly et al. (2012) [62] Developed an autonomous software based on multi-agent technology
316 to detect any malfunctioning in the system. The software is modularly integrated into the monitoring system to
317 monitor the installed sensor. A e-mail notification were automatically composed and immediately send to the
318 responsible personnel. As a result appropriate actions were undertaken in time.

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

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

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

335 Schlechtingen, Meik et al (2012) [66] in their approach employed Neuro-Fuzzy interface system (ANFIS) models
336 in training phase. Then trained models applied to product predict the target signals in application phase eg.

337 Temperature, pressure, currents etc. The normal or abnormal behavior of component can be indicated by
338 prediction error with respect to learned behavior. This method is applied to 18 onshore wind turbines of 2MW
339 and results shows that proposed method is well suited to closely monitor a large variety of signals. The accuracy
340 of developed model is high hence even a small behavior changes can be detected. Robert B. Randall et al. (2012)
341 [68] presented a work in which a number of ways for compensating for speed and load variations on basis of
342 obtained signals from study of natural occurring faults in wind turbine transmission were discussed. The gearbox
343 was mounted on a test rig and a "pseudo-encoder" signal is extracted from a vibration signal.

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

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

352 to develop the first monitoring model and other two are developed by using the concept of control chart for
353 detecting abnormal values of drive train and tower acceleration.

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

358 Walter Bartelmus (2012) [67] present a new way of diagnostic which is based on object and operation factor
359 oriented analyses. The data is presented in the term of susceptibility characteristics. The system shows two types
360 of susceptibility. With increase in load mean value of generated vibration given by acceleration signal increases,
361 and change in object condition, create a eristics. parallel shift of susceptibility charact [72] presented a work to
362 determine the influence of the gyroscopic couple on dynamic behavior of blades made of glass fiber reinforced
363 (GRP).

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

368 Jin Zhang et al. (2012) [74] state that impulses in vibration signals and their spectral features are the key
369 indicators for diagnosing gear damages. They proposed a new method time wavelet energy spectrum for extracting
370 characteristic frequency of faulty gears. The experimental results shows that this method can highlight impulses
371 and is very effective for extracting repeating frequency of periodic impulses and it can even extract the weaker
372 fault feature of gear tooth wear. Mohamed Boufenar et al. (2012) [75] presented a work in which they study,
373 compare and modify the time frequency representation techniques such as Wigner Ville Distribution(WVD),
374 Short Time Fourier Transformation (STFT) and wavelets to analyses non stationary phenomena.

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

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

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

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

392 Michael Wilkinson et al. (2013) [80] proposed that operational costs get greatly reduced by monitoring the
393 condition of major components in the drive train. They conduct the validation study on this method using
394 five wind farms and conclude that a good detection accuracy and high detection rate is possible. Dr. Shaik
395 Nafeez Umar et al. (2013) [81] apply acoustic emission technique for condition monitoring of wind turbine
396 and they conclude that AE technique can be successfully applied for condition monitoring of low speed rotating
397 components. They observed that technique is able to detect very small energy release rates due to incipient
398 failure at starting stage.

399 Schlechtingen, et al. (2013) [82] present a system for wind turbine condition monitoring by using adaptive

400 Neuro-Fuzzy interference systems (ANFIS). To fulfill the purpose a normal behavior model for common SCADA
401 are developed to detect abnormal signals.

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

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

412 Tommi [85] point out that there is no generally accepted widely deployed condition
413 monitoring method for power converters. Thus in this study they investigate the benefit and desirability of
414 condition monitoring for electronic converter.

415 Ridha Ziani et al. (2012) [71] presented a work in which they compare the performance of bearing fault
416 detection by using Artificial Neural Network (ANN) and Genetic algorithm (GA). The time domain signals from
417 normal and defective gear boxes are extracted and used as input to ANN. The system features are selected on
418 the basis of genetic algorithm and linear Discriminant analyses (LDA) is used as evolution function. Summary
of Literature Survey ^{1 2}



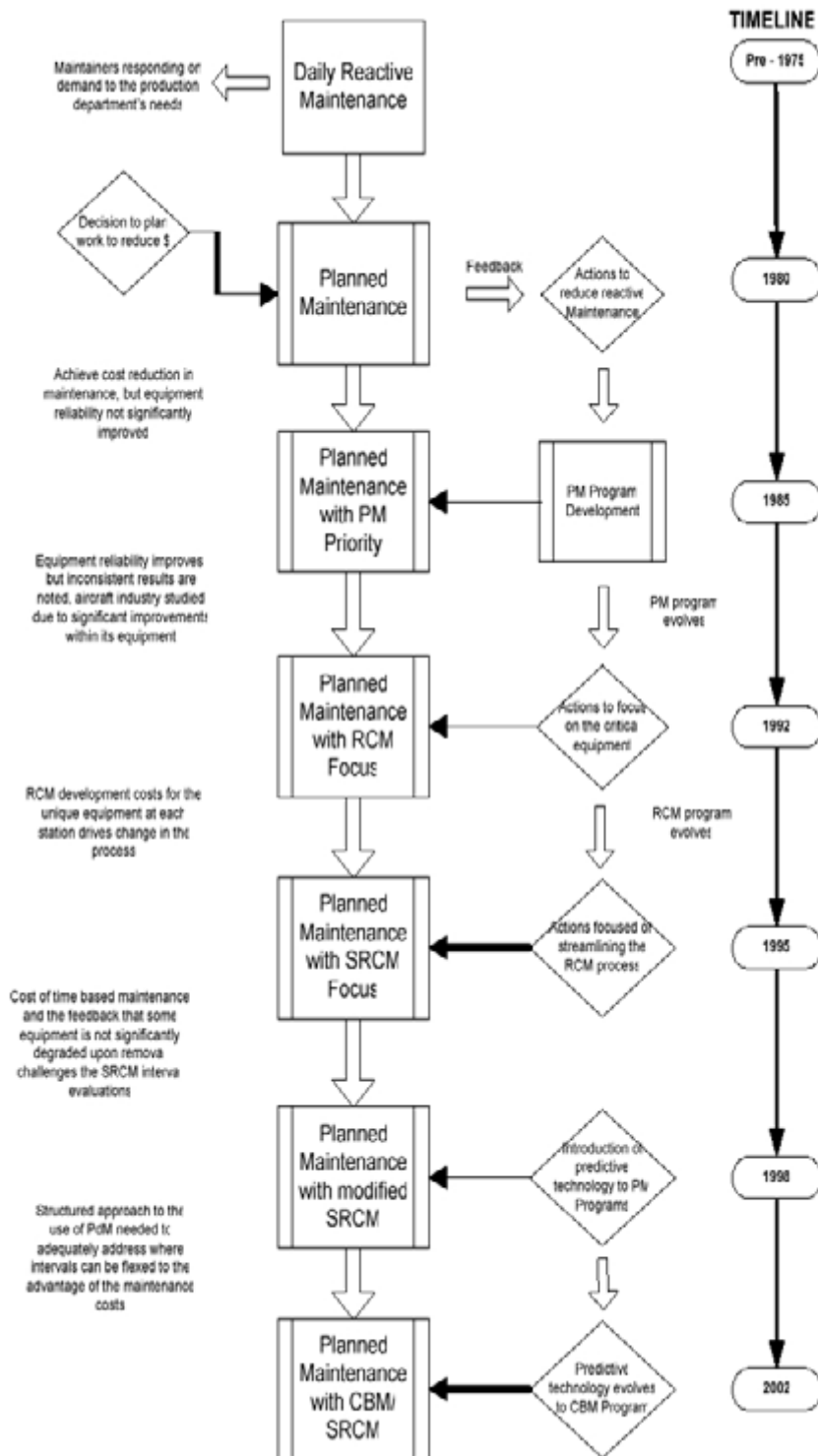
11

Figure 1: Figure 1 . 1 :

419

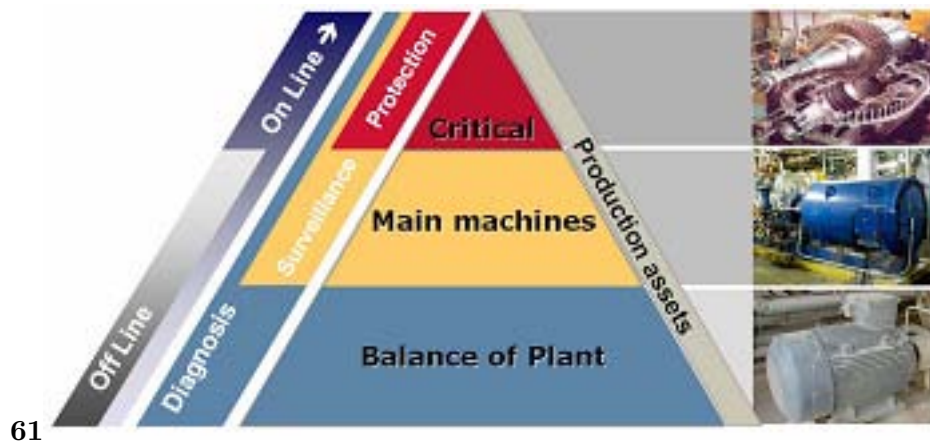
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1

Figure 2: Figure 1



61

Figure 3: Figure 6 . 1 :



Figure 4: Condition



2

Figure 5: 2 ©

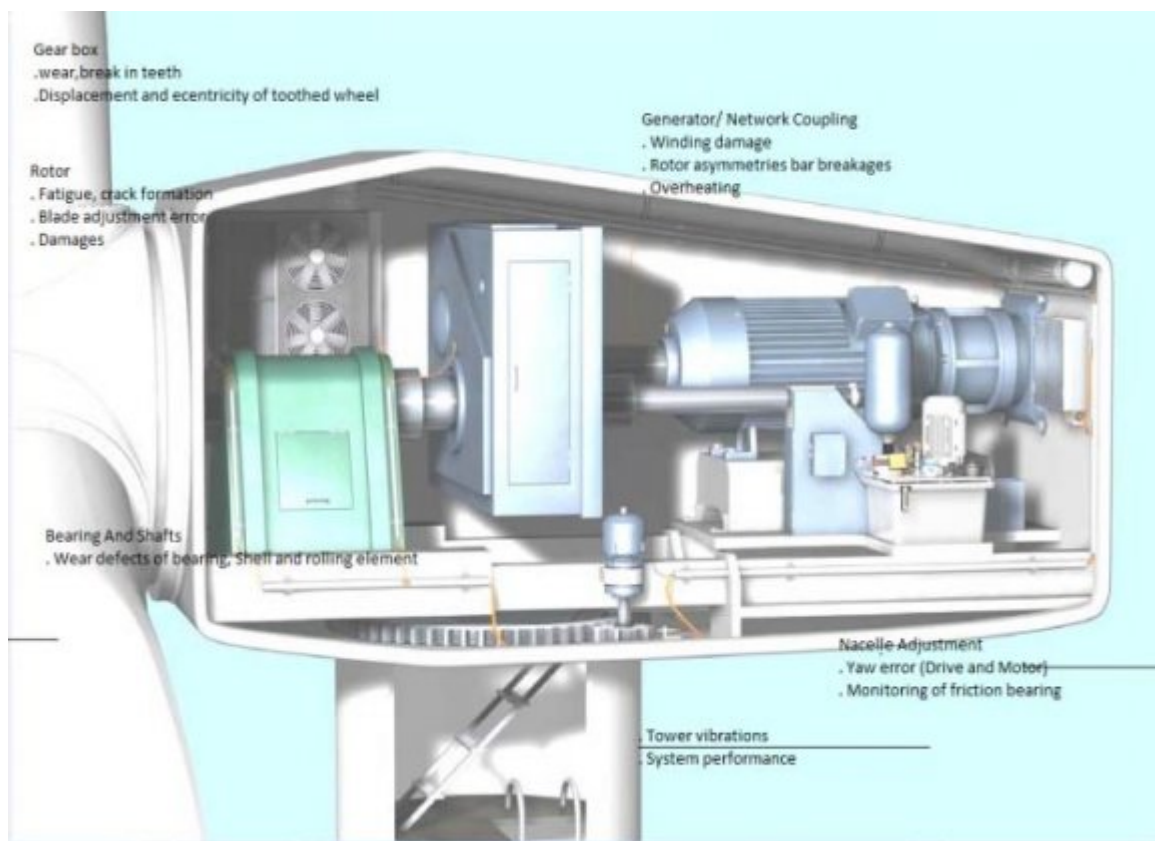


Figure 6: Condition

3

| Field# | Linked to Result | 1 : Steps involved in preliminary p | Comments |
|--------|------------------|-------------------------------------|----------|
| 1 | | 4 | 2 |
| 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.

Figure 7: Table 3 .

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

Figure 8: Table 3 .

Ayetullah Gunel et al. (2007)

Figure 9:

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.

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

| Refno. | Author(s) | Investigated Problem Type |
|--------|---------------------------------------|---|
| | | Year |
| | Palle Christensen et al.(2001) | Automatic supervision and control of wind turbines |
| | T. Holroyd (2001) | Defect of varying size on outer races of bearings. |
| | N.Jamludin et al. (2001) | Stress wave analyses to detect early stages damages |
| | Shjn Dander (2002) | Time domain model based fault detection |
| | T.W. Verbruggen (2003) | Develop inventory of available condition monitoring techniques |
| | L. Mihet-Popa et al. (2003) | Steady state technique for detection of interturn stator faults |
| | L.W.M.M. Rademakers et al. (2004) | Condition monitoring of fibers blades |
| | Giurgiutiu,V (2005) | Fault detection method based on ultrasonic rely |
| | Douglas H. (2005) | Fault detection in Doubly Fed induction generator |
| | Christopher A. Walfard (2006) | Reliability of wind power generation |
| | C. Walfard (2006) | Cost estimation of failure of wind turbine |
| | R.W. Hyers et al. (2006) | Comparison of CM techniques of turbine and helicopter gearbox |
| | Jesse A. Andrawus et al. (2007) | Detection of wind turbine faults using RCM |
| | David Mc Millan et al. (2007) | Measurement of benefits of CM quantitatively |
| | Ayetullah Gunel et al. (2007) | Fluid condition monitoring technique |
| | Michael Wilkinson et al. (2007) | Selection of sensors and algorithm |
| | Edwin Wiggelinkhuizen et al. (2007) | Algorithm based on SCADA |
| | German wind energy association (2007) | Requirement of a CM plan |
| | Michael R. Wilkinson (2007) | Signal Processing technique |
| | R.Andrew Swaetz et al. (2008) | Dynamic behavior and loading of wind turbine |
| | Scott. J. Johnson et al. (2008) | Active flow control |
| | Mike Woebeking (2008) | Percentages of various type of damages responsible for failure |
| | Asif Saeed (2008) | Fault detection by signal processing techniques |
| | William A. Vachon (2008) | Project Economics |
| | E Lie-Ahmar et al. (2009) | Transient Techniques |
| | Cattin Rene et al. (2009) | CM techniques for wind turbines in icy regions |
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| | T. Barszczet et al. (2009) | Fault detection by Neural Network approach |
| | R.F. Mesquita et al. (2010) | Fault detection by Neural Network approach |
| | Emilio Miguelanez et al. (2010) | Role of See Byte's Recovery system in wind industry |
| | Bincheng Jiang (2010) | Dynamics behavior of gear boxes in transient conditions for fault detection |
| | Wenxian Yang et al. (2010) | Continuous Wavelet Transform |
| | Yassine Amirat et al. (2010) | Fault detection based on amplitude demodulation of three phase generator |
| | Milos Milovancevic (2010) | Dynamic load behavior and streamlining |
| | Joon Young et al. (2010) | Designing of a new simulator |
| | Eunshin Byon et al. (2010) | Effect of weather conditions on feasibility of maintenance |
| | Diabul D. et al. (2010) | Characterization of debris and debris flow of |

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