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Cost Optimization of Maintenance Scheduling for Wind Turbine Gearbox Components with Assured Reliability

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Abstract The operation of a particular component in deteriorating condition will lead to a high machine downtime. This is due to the failure of component at unexpected time. As a result it will increase cost of maintenance and production lost. One of the solutions to this matter is to use Preventive Replacement (PR). PR is one of the maintenance optimization strategies that can balance the failure cost in unexpected time (maintenance and production lost) and maintenance benefits (minimize downtime) for a deteriorating component. Therefore, the objective of this paper is to introduce the PR strategy for determining an optimal replacement time for component that deteriorates over time. The models are used for the cost per unit time based on the stochastic behavior of the assumed system. The model reflects the cost of storing a spare as well as the cost of system downtime. The minimum-cost (optimum) policy time is calculated with the consideration of availability. It is noted that all maintenance cost results converge to the optimal value of the age replacement policy which has the same configuration when inspection interval increases.

Keywords: *maintenance, preventive maintenance, availability limit, maintenance cost optimization, replacement policy*

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1. Introduction

Generally, the condition-based preventive maintenance (PM) policy is more efficient than a PM policy based only on the system age and on the knowledge of the statistical information on its lifetime [1,2]. However, as stressed in [1], the price for this higher efficiency is the requirement of a mathematical model for the stochastic deterioration process of the maintained system. There is an economic necessary to quantify and model the deterioration / maintenance process, because this model can be used by the maintenance decision-maker as a tool to optimize the maintenance decisions and to minimize the total maintenance cost of the system. Usually, the task of deriving such a mathematical model is more complicated than just statistically describing the binary transition from a "good state" to a "failed state". An age-replacement model has been consider with minimal repair based on a cumulative repair cost limit and random lead time for replacement delivery. A cumulative repair cost limit policy uses information about a system's entire repair cost history to decide whether the system is repaired or replaced; a random lead time models delay in delivery of a replacement once it is ordered.

A predictive-maintenance structure for a gradually deteriorating single-unit system (continuous time / continuous state) was presented in [3]. The proposed decision model enables optimal inspection and replacement decision in order to balance the cost engaged by failure and unavailability on an infinite horizon. Two maintenance decision variables were considered: the preventive replacement threshold and the inspection schedule based on the system state. In order to assess the performance of the proposed maintenance structure, a mathematical model for the maintained system cost is developed using regenerative and semi-regenerative processes theory. Numerical experiments showed that the expected maintenance cost rate on an infinite horizon can be minimized by a joint optimization of the replacement threshold and the periodic inspection times. The proposed maintenance structure performs better than classical preventive maintenance policies which can be treated as particular cases. Using the proposed maintenance structure, a well-adapted strategy can automatically be selected for the maintenance decision-maker depending on the characteristics of the wear process and on the different unit costs.

Dealing with stationary degradation signals. In reality, signals from wind turbines are often non-stationary as large wind turbines often operate at variable speeds. The wavelet transform seems more appropriate in handling non-stationary signals. In [4], a life cycle cost approach is adopted to evaluate the financial benefit using condition monitoring system, a tool for implementing CBM policy, while in [5], a multi-state Markov decision process is used to estimate the wind turbine degradation process based on which the optimal maintenance scheme is devised. By leveraging condition monitoring information, CBM is expected to reduce the operation and maintenance costs of wind power generation systems. Existing CBM methods for wind power generation systems deal with wind turbine components separately, that is, maintenance decisions are made on individual components, rather than the whole system. However, wind farms are often, located in remote areas or off-shore sites. Each wind farm consists of multiple wind turbines, and each wind turbine has multiple components including main bearing, gearbox, generator, shafts, etc. Obviously, there are economic dependencies among wind turbines and their components. That is, once a maintenance team is sent to the wind farm, it may be more economical to take the opportunity to maintain multiple turbines. If a turbine is stopped for maintenance, it may be more economical to replace or repair multiple components which have shown high risks of failures.

A condition-based maintenance model for continuously degrading systems under continuous monitoring was considered in [6,7]. After maintenance, the states of the system are randomly distributed with residual damage. A realistic maintenance policy was investigated, referred to as condition-based availability limit policy, which achieves a maximum availability level of such systems. The optimum maintenance threshold was determined using a search algorithm. Units operating under normal conditions may experience random failures and cease functioning abruptly. This type of failures was referred to as "hard" failures. However, there are situations where units experience degradation in its function (or performance) until its degradation measure reaches a predetermined failure threshold where it is considered failed as a "soft" failure.

Gearbox system reliability is a critical factor in the success of any industrial project. Poor reliability directly affects both the project's revenue stream through increased operation and maintenance (O&M) costs and reduced availability to the system due to its downtime. Indirectly, the acceptance of the system by the financial and developer communities as a viable enterprise is influenced by the risk associated with the capital equipment reliability; increased risk, or at least the perception of increased risk, is generally accompanied by increased financing fees or interest rates. A reliability which based on a developed an analytical mathematical method for predicting remaining lifetime of cracked gear tooth was explored. The development is focused specifically on the investigation of a generalized statistical method for characterizing and predicting system Weibull density function degradation (hazard rate). Using this method, optimal preventive age replacement policy is determined to maximize gearbox system reliability, and consequently an optimal cost analysis can be estimated. A simple geared system is used as a medium for real data collection, where the torsional vibration acceleration was measured and analyzed. The results indicate that the knowing of the remaining lifetime and the optimized replacement cost of the faulty gear can enhance the process of scheduling maintenance, order spare parts and using resources; consequently reduce maintenance cost [8,9].

In this paper, a generalized age-replacement policy based on a cumulative repair cost limit is used, and the random lead time for replacement is also considered. A model is used for the average cost per unit time based on the stochastic behavior of the assumed system. The model reflects the cost of storing a spare as well as the cost of system downtime. The minimum-cost policy (optimum) time is calculated with the consideration of availability. The wind turbine gearbox components faults considered are planet gear tooth crack, planet gear tooth spalling, planet gear tooth breakage, planet gear carrier crack, and main bearing inner race crack.

2. Condition Based Maintenance (CBM) Scheme

To fulfill the goal of prognostics, three crucial steps are needed. At first, the defect or abnormality should be able to be detected at its early stage. Secondly, the component or system performance needs to be assessed robustly and tracked continuously. Finally, a prediction with confidence interval needs to be generated estimating the remaining useful life and possible failure mode of the machine or system. Furthermore, a generalized age-replacement policy based on a cumulative repair cost limit is used. The Condition based- Maintenance (CBM) system scheme Figure 1.

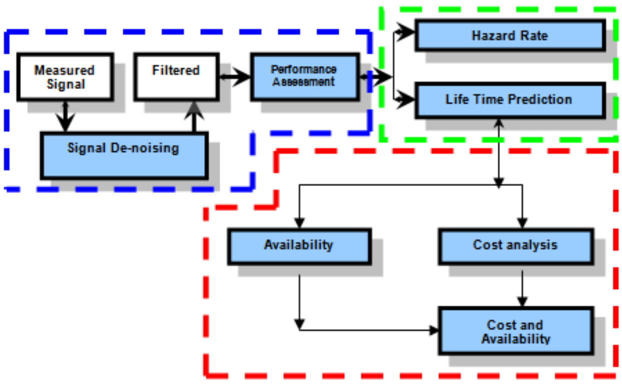

Figure 1. The Condition based- Maintenance (CBM) system scheme

3. Measured and Filtered Signals Determination

The experimental set-up consists of 15 horsepower (hp), 1440 rev/min AC drive motor and inverter (speed controller) represent the system output, while a hydraulic brake represents the input from the wind. The motor, hydraulic disc brake and gearbox are hard-mounted and aligned on a bedplate. The bedplate is mounted using isolation feet to prevent vibration transmission to the floor. The establishment of the experimental methodology and the accelerometers positions are presented in detailed in [10], where the measuring of rotational response has been evaluated by using a pair of matched accelerometers placed a short distance apart on the gearbox's structure. Tests were conducted in order to calibrate the sensor configuration and insure the reaptability of the recordings and the proper operation with minimum noise of the system as well as the various cables and connections.

Faults with their dimensions have been artificial made in the wind turbine gearbox components are tabulated in Table 1. Figure 2 shows the planetary gearbox assembly. Figure 3 shows photograph of test layout, while Figure 4 shows the accelerometers postions. Figure 5 and Figure 6 show an example of healthy and such fault for main bearing respectively. The motor speed controller allows tested gear operation in the range of 20-40 rpm. The load is provided by a hydraulic brake connected to the load motor. The speed of the drive motor and the load can be adjusted continuously to accommodate the range of speed/torque operating conditions. The faults were made artificially with wire electrical discharge machining (EDM) and chemical electrode on the gearbox to create a stress concentration which eventually led to a propagating fault. This type of test was preferred in order to have the opportunity to monitor bath faults modes, i.e., the natural fault propagation.

Table 1. Wind turbine planetary gearbox faults dimensions

	Defect Type	Defect Dimensions
0	Healthy gearboxes	Free from defects
1	Planet gear tooth crack	Depth 1.0 mm Thickness 0.2 mm
2	Planet gear tooth Spalling	Spalling length = 0.9 mm Spalling height = 1 mm Spalling width = 4.6 mm
3	Planet gear tooth breakage	Breakage thick = 0.6 mm, Breakage width = 4.6 mm Breakage height = 1.35 mm
4	Low speed shaft (LSS) Main bearing crack	Depth 1.0 mm Thickness 0.2 mm
5	Planet gears carrier crack	Depth 1.0 mm Thickness 0.2 mm

Figure 2. Planetary gearbox assembly

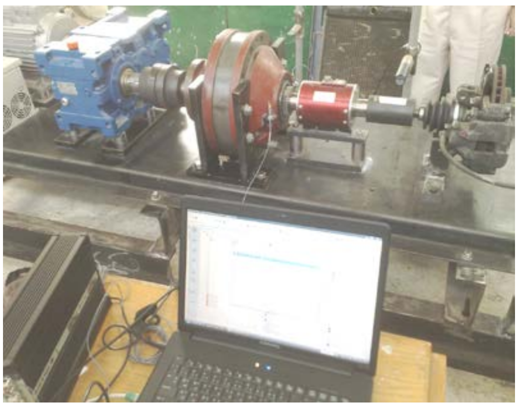

Figure 3. The experimental set-up

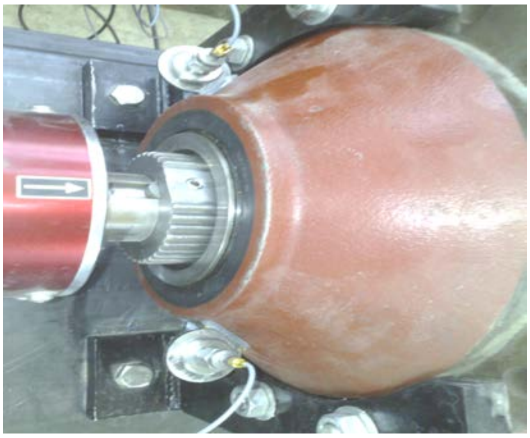

Figure 4. Position of the accelerometers

Figure 5. Main bearing in healthy condition

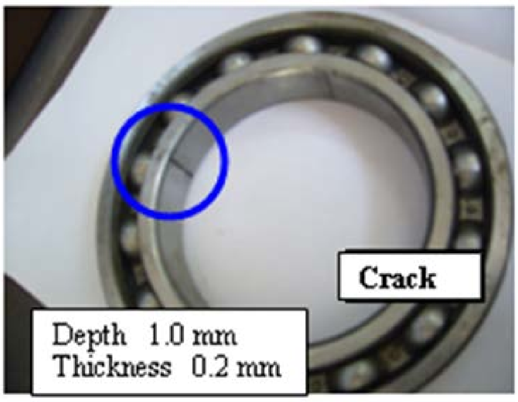

Figure 6. Main bearing inner race crack

The vibration is measured with two Bruel & Jeer accelerometers mounted on the gearbox housing in the rotational direction of fault action, one in each side-axis. The signals from both accelerometers are properly amplified, filtered. The sampling frequency used was 6.0 kHz and signals of 1.0 sec duration were recorded. B&K portable and multi-channel PULSE analyzer type 3560-B-X05 is used with the B&K PULSE lab shop which is the measurement software type 7700. The results then fed into the computer for further processing. The speed is measured by a photo electric probe. Recordings were carried out at constant speed. After acquiring the measured vibration signals in the time domain as described above, it is processed to obtain feature vectors (filtered signals). The continuous wavelet transform (CWT) is used for obtaining the wavelet coefficients of the signals. The statistical parameters of the wavelet coefficients are extracted which constitute the feature vectors [11].

4. Proportional Hazard Model

A widely used proportional hazard model (PHM) combines a Weibull probability density function baseline hazard function with a component the covariates which affect the time to failure, which is shown as follows [12]:

$$h(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{1}$$

where

h(t): is the hazard value, or failure rate value, at time t . The right hand side in equation (1) is the baseline hazard function, which takes into account the age of the component at time of inspection, given the values of parameter β and η. Furthermore, it is considered to be the key condition monitoring measurements reflecting the health condition of the component.

η : is the characteristic life or is the scale parameter.

β : is the shape parameter.

5. Optimum Maintenance Policy for Replacement

5.1. Age Replacement Cost Model

The classical policy used in maintenance application is called failure replacement policy, or age replacement (ARP). Under a preventive maintenance policy, the replacement of the component is either made after a specified time interval or in the case of component failure before the next scheduled time for replacement. The idea of this maintenance strategy is to replace the component with a new one (i.e. maximal repair) when it fail or when it has been in operation for T_p time units, whichever comes first. The expected maintenance cost per unit time, C, can be written as [13]:

$$C(T_p) = \frac{C_p R(T_P) + C_c F(T_p)}{\int_0^{T_P} R(t)dt} \tag{2}$$

5.2. Maintenance Cost Minimization

The profit and loss statement of a company recognizes good performance as low, per unit, production cost .Therefore, a hazard level intervention point states in previous sections that results in low cost has to be chosen. Intuitively, a policy resulting in very low hazard will be expensive has surmised. On the other hand, choosing to operate at a very high hazard will approach the cost of ignoring hazard and running to failure. It is concluded that there must be a best policy some where between the two extremes. To complete the CBM decision process an additional relationship needs to be find. The relationship between hazard rate and significant operational (condition monitoring) data needs to be established.

5.3. Availability Model

Availability deals with the duration of up-time for operations and is a measure of how often the wind turbine planetary component is alive and well. It is often expressed as (up-time)/(up-time + downtime) with many different variants. Up-time and downtime refer to dichotomized conditions. Up-time refers to a capability to perform the task and downtime refers to not being able to perform the task, i.e., uptime = not downtime. Availability issues also deal with at least three main factors [14,15]: 1) increasing time to failure, 2) decreasing downtime due to repairs or scheduled maintenance, and 3) accomplishing items 1 and 2 in a cost effective manner. As availability grows, the capacity for making money increases because the component is in service a larger percent of time.

A maximum availability model is one of the three options for the selection of an optimal predictive maintenance strategy. The parameters of this strategy must to be considered. They are fixed values for the downtimes incurred by:

1. preventive renewal (maintenance), and
2. renewal as a result of failure.

The costs of materials and labor are not considered significant in this model, or they are believed to be proportional to downtime and, thus, can be ignored.

$$AV(T_p) = \frac{\int_0^{T_P} R(t)dt}{\int_0^{T_P} R(t)dt + t_p R(T_P) + t_c F(T_p)} \tag{3}$$

where:

AV (T_p): is availability

t_p: is preventive replacement downtime

t_c: is failure replacement downtime

In a symmetrical way, the maximum availability model focuses completely on downtime. In this report, high availability had bought by paying for it with more frequent intervention. It is assumed that the cost of repair was negligeable, or was proportional to the cost, and therefore could be ignored. The difference between failure and preventive repair times (rather than costs) dictated the exact nature of the compromise to achieve high component availability.

5.4. Maintenance Cost and Availability Combined Model

The combined cost and availability optimization option is used to minimize expected maintenance cost per unit time taking into account costs and duration of preventive and failure downtimes, and cost of downtime. This cost model allows for flexibility in setting up realistic parameters upon which to build the optimal decision model. For example

1- the fixed cost of failure replacement may be high (say due to the cost of a new part), but the downtime required may be short (just to replace the part). Or, by comparison, the situation may be that:

a) the cost of preventive work can be small, but

b) the time to complete the work (downtime) can be long.

This model resolves the extremely difficult problem of deciding upon maintenance policies in the light of actual maintenance costs. The expected maintenance cost and availability per unit time, C + AV, can be written as [16]:

$$C(T_p)+AV(T_p)=\frac{(C_p+a_pt_p)R(T_P)+(C_c+a_ct_c)F(T_p)}{\int_0^{T_P} R(t)dt+t_pR(T_P)+t_cF(T_p)} \quad (4)$$

where:

$C(T_p)$ + $AV(T_p)$: is maintenance cost function and availability combined

a_p: is hourly preventive replacement cost per unit time

a_c: is hourly corrective (failure) replacement cost per unit time

6. Results and Discussion

6.1. Maintenance Cost Estimation

The Optimal Decision Policy: is defined as one that minimizes the average cost per unit working age of replacements (preventive and failure maintenance). An estimation of the costs of failure replacement and preventive replacement of 20000 L.E. and 4000 L.E. respectively are used [4]. Alternatively, if maximum asset availability were the required optimization objective, one might apply a mean time to return to service. Six test cases (one healthy and five faults), covering different wind turbine planetary gearbox component faults, are considered to illustrate their maintenance costs.

Table 2 tabulates the hazard lifetime data obtained from the measured rotational vibration responses in its filter form based on the procedure stated in previous section. Samples of these data for planet gear tooth crack fault at speed 20 rpm - torque load 20 Nm and 40 rpm - 40 Nm and filtered based on the concept stated in [10] for all the type of tests considered in this work. The filtered signals are used in equation (1), where the hazard lifetimes (LT) are estimated based on the weibull distribution with assured reliability changed and the change in both speed and torque load, which decreased as the speed and torque load increased and tabulated in Table 2 along the values of the scale parameter and shape factor obtained from the interpretation of the measured rotational vibration results for all the tests considered in this work. Samples of these results for healthy gearbox and main bearing inner race fault are shown in Figure 7 and Figure 8 respectively and tabulated in Table 2. It is indicated that the value of the RMS at failure based on the Weibull distribution with assured reliability changed and the change in both speed and torque load, which decreased as the speed and torque load increased. The shape factor and scale parameter values for the healthy gearbox are taken from [3]. It can be seen that the hazard lifetime (LT) at failure worked effectively. It captured the system behavior exactly and gives an alarm signal about possible irregularity before the component actually broke. That is a very valuable indication for the gear system health condition monitoring. The results also show that the determination of the lifetime (LT) at failure is effective in estimating the progress of the prognostic process well in advance of the impending catastrophic failure. The same discussion can be applied on the rest of the wind turbine planetary gearbox components faults considered.

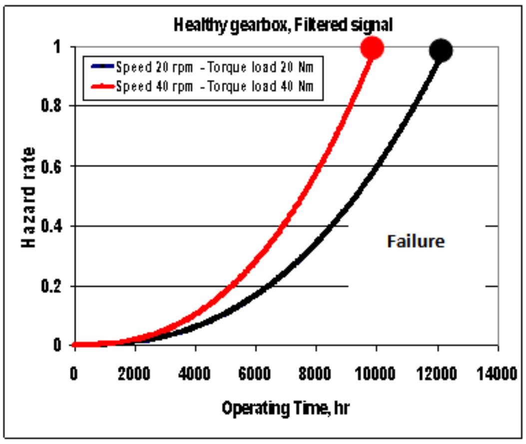

Figure 7. Hazard lifetime (LT) at failure, healthy gearbox

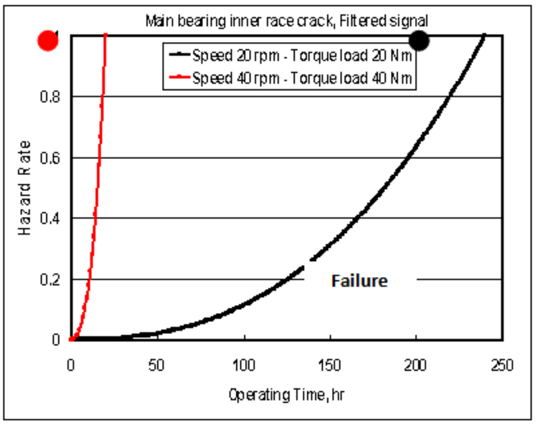

Figure 8. Hazard lifetime (LT) at failure, main bearing inner race crack

Table 2. Single number of the scale parameter, shape factor and filtered signal lifetime (LT) values

No.	Speed – Torque load, (rpm-Nm)	Planetary Gearbox Component Faults	Shape Factor,β	η Value	LT Value
				hrs	
1	20 rpm – 20 Nm	Healthy gearbox	3.5	12300	12300
2		Planet gear crack	3.5	400	400
3		Planet gear spalling	3.5	225	226
4		Planet gear breakage	3.5	35	35
5		Planet gears carrier crack	3.5	160	210
6		Main bearing inner race crack	3.5	240	240
7	40 rpm – 40 Nm	Healthy gearbox	3.5	10000	10000
8		Planet gear crack	3.5	210	211
9		Planet gear spalling	3.5	18	19
10		Planet gear breakage	3.5	22	21
11		Planet gears carrier crack	3.5	180	180
12		Main bearing inner race crack	3.5	20	20

LT: Lifetime η : is the characteristic life or is the scale parameter

Maintenance Cost: of the wind turbine gearbox for all six test cases considered in this work, where examples of healthy gearbox and main bearing inner race crack conditions in the range of hazard lifetime (LT) determined based on equation (2) and tabulated in Table 3 and Table 4. In healthy gearbox, Figure 9 shows the values of the maintenance cost data at failure point with 20 rpm, 20 Nm condition (Table 3) for filtered signal is 2.852 L.E./hr at 12300 hr, while the values at optimum point in 20 rpm, 20 for filtered signal is 1.405 L.E./hr at 4034 hr. In the case of 40 rpm, 40 Nm condition (Table 4), the values of the maintenance cost data at failure point for filtered signal is 3.508 L.E./hr at 10000 hr, while the values at optimum point for filtered signal is 1.728 L.E./hr at 3267 hr. Moreover, the main bearing inner race crack the values of the maintenance cost and depicted in Figure 10 and the data at failure point with 20 rpm, 20 Nm condition (Table 3) for filtered signal is 145.43 L.E./hr at 240 hr, while the values at optimum point in 20 rpm, 20 Nm condition for filtered signal is 71.19 L.E./hr at 80 hr. In the case of 40 rpm, 40 Nm condition (Table 4), the values of the maintenance cost data at failure point for filtered signal is 1679.9 L.E./hr at 20 hr, while the value at optimum point for filtered signal is 749.66 L.E./hr at 5 hr. The same discussion can be applied on the rest of the wind turbine planetary gearbox components faults considered.

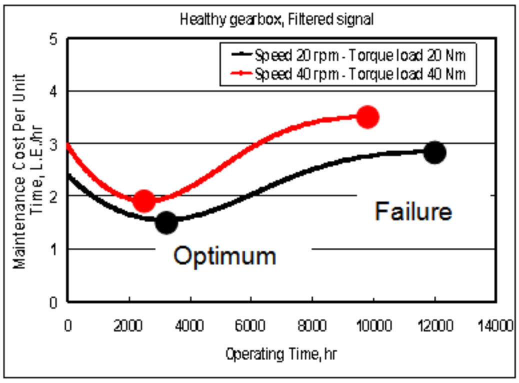

Figure 9. Maintenance cost, healthy gearbox

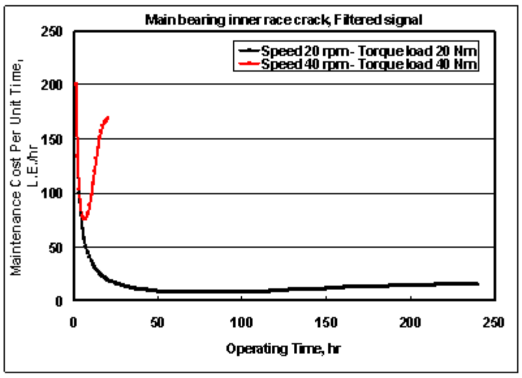

Figure 10. Maintenance cost,main bearing inner race crack

Table 3. Summarized maintenance cost, availability, and maintenance cost and availability for filtered signal, speed 20 rpm – torque load 20 Nm

No.	Replacement Policy	Total Cost			Availability		Cost and Availability		
		Value L.E/hr	Time hr	Total L.E	Value	Time hr	Value L.E/hr	Time Hr	Total L.E
1	Healthy gearbox								
	At Failure	2.852	12300	35079.6	0.3629	12300	2.850	12300	35055
	Optimal	1.405	4034	5677.8	0.4588	4851	1.545	2963	4577.84
	Saving,%	50.7	67.72	83.8	26.4-	60.56	49.3	75.91	86.9
2	Main bearing inner race crack								
	At Failure	145.43	240	34903.2	0.572	240	167.8	240	40288.8
	Optimal	71.19	80	5695.2	0.830	97	82.06	80	6564.7
	Saving,%	51.74	66.66	83.68	-45.15	59.58	51.11	66.7	83.70

(-) refers to value increase

Table 4. Summarized maintenance cost, availability, and maintenance cost and availability for filtered signal, speed 40 rpm – torque load 40 Nm

No.	Replacement Policy	Total Cost			Availability		Cost and Availability		
		Value L.E/hr	Time hr	Total L.E	Value	Time hr	Value L.E/hr	Time Hr	Total L.E
1	Healthy gearbox								
	At Failure	3.508	10000	35080	0.3529	10000	3.506	10000	35060
	Optimal	1.728	3267	5645,4	0.4594	3915	1.8964	2540	4816.8
	Saving,%	50.7	67.33	83.9	-30.3	60.85	45.9	74.90	86.3
2	Main bearing inner race crack								
	At Failure	1679.9	20	33598	0.373	20	1676.7	20	33534
	Optimal	749.66	5	3748.3	0.502	7	820.59	5	4100
	Saving,%	55.37	75.00	88.84	-34.58	65.00	51.06	75.00	87.77

(-) refers to value increase

The Achieved Availability and Downtime: may include the time of corrective (failure) maintenance, corrective replacement, preventive (optimum) maintenance and preventive replacement. In order to develop a realistic maintenance policy, the effectiveness of the maintenance policy by calculating the availability of the system is assessed. Maintenance cost of the wind turbine gearbox for all six test cases considered in this work, where examples healthy and main bearing inner race crack conditions in the range of hazard lifetime (LT) determined based on equation (3) and tabulated in Table 3 and shown in Figure 11 and Figure 12 illustrate the values of the availability data at failure and optimum points. In the maintenance cost model, it is bought lower cost by paying for it with more frequent intervention. It is assumed that the time -to- repair was negligible, or was proportional to the cost, and therefore could be ignored. The difference between failure and optimum maintenance costs dictated the exact nature of the compromise in other that overall impact on the per unit production cost be minimum. In the symmetrical way, the maximum availability model focuses completely on downtime. In these figures, high availability has been bought by paying for it with more frequent intervention. It is assumed that the cost of maintenance was negligible, or was proportional to the repair time and therefore could be ignored. The difference between failure and preventive (optimum) repair times (rather than costs) dictated the exact nature of the compromise to achieve high gearbox component availability in the range of component hazard lifetime (LT) presented in Table 2. It is indicated that in the case of healthy gearbox, where the data shown in Figure 11 which estimated the values of the availability data at failure point with 20 rpm, 20 Nm condition (Table 3) for filtered signal is 0.3629 at 12300 hr, while the values at optimum point is 0.4588 at 4851 hr. In the case of 40 rpm, 40 Nm condition (Table 4 and Figure 12), the values of the maintenance cost data at failure point for filtered signal is 0.3529 at 10000 hr, while the values at optimum point for filtered signal is 0.4594 at 3915 hr. Moreover, the main bearing inner race crack the values the of the availability data at failure point with 20 rpm, 20 Nm condition (Table 3) for filtered signal is 0.572 at 240 hr, while the values at optimum point in filtered signal is 0.830 at 97 hr. In the case of 40 rpm, 40 Nm condition (Table 4), the values of the availability data at failure point for filtered signal is 0.373 at 20 hr, while the values at optimum point for filtered signal is 0.502at 7 hr. The time for the wind turbine planetary gearbox component to reach the threshold after maintenance actions and before replacement may be decreasing due to aging; more frequent maintenance actions and longer maintenance times are required to keep the gearbox operating. In other words, the average short-run availability of the system will be decreasing since the expected uptime decreases whereas the expected downtime increases. The same discussion can be applied on the rest of the wind turbine planetary gearbox components faults considered.

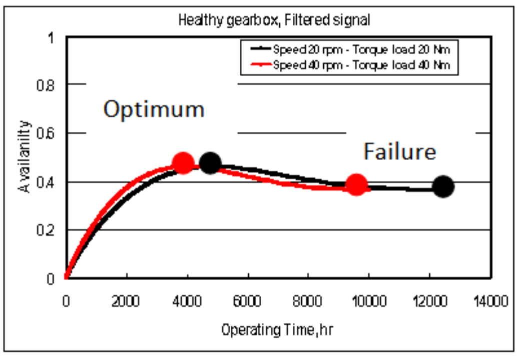

Figure 11. Availability, healthy gearbox

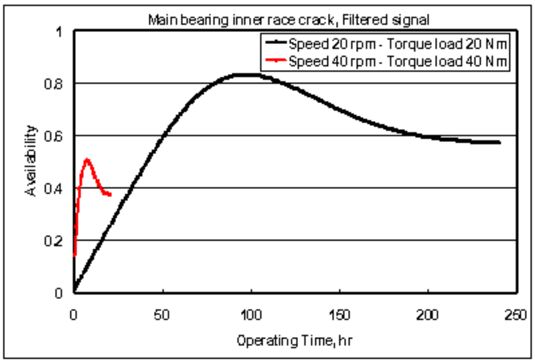

Figure 12. Availability main bearing inner race crack

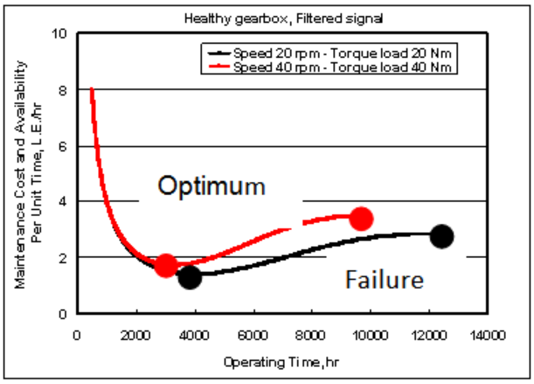

Figure 13. Maintenance cost and availability, healthy gearbox

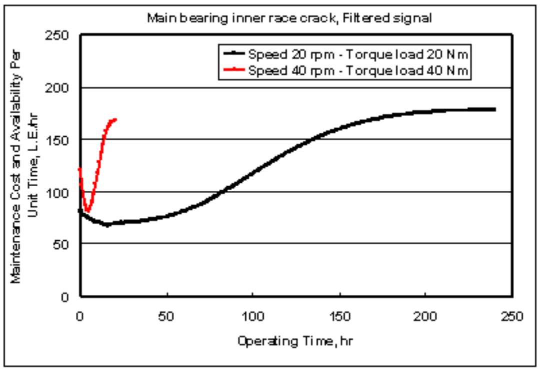

Figure 14. Maintenance cost and availability,main bearing inner race crack

Maintenance Cost and Availability: of the wind turbine gearbox for all six test cases considered in this work, where examples healthy and main bearing inner race crack conditions. The difference between failure and preventive (optimum) repair times (rather than costs) dictated the exact nature of the compromise to achieve high gearbox component cost and availability. in the range of hazard lifetime (LT) determined based on equation (4) and tabulated in Table 3. In healthy gearbox, Figure 13 and Figure 14 show the values of the maintenance cost and availability data at failure and optimum points**.** It is indicated that in the case of healthy gearbox, where the data shown in Figure 13 which estimated the values of the maintenance cost and availability data at failure point the values of the maintenance cost and availability, L.E./hr, data at failure point with 20 rpm, 20 Nm condition for filtered signal is 2.850, L.E./hr, at 12300 hr, while the values at optimum point in 20 rpm, 20 Nm condition (Table 3) for filtered signal is 1.545, L.E./hr, at 2963 hr. In the case of 40 rpm, 40 Nm condition (Table 4), the values of the maintenance cost and availability data at failure point for filtered signal is 3.50 at 10000 hr, while the values at optimum point for filtered signal is 1.8964 at 2340 hr. Moreover, the main bearing inner race crack the values the of the maintenance cost and availability data at failure point with 20 rpm, 20 Nm condition (Table 3 and Figure 14) for filtered signal is 167.87 L.E./hr, while the values at optimum point in filtered signal is 82.059 L.E./hr at 80 hr. In the case of 40 rpm, 40 Nm condition (Table 4), the values of the maintenance cost and availability data at failure point for filtered signal is 1676.7 at 20 hr, while the values at optimum point for filtered signal is 820.59 at 5 hr. The same discussion can be applied on the rest of wind turbine planetary gearbox components faults. Table 3 and Table 4 summarize the values of maintenance cost, availability and maintenance cost, and availability for filtered signals, where the speed-torque load are 20 rpm, 20 Nm and 40 rpm, 40 Nm respectively. It can be seen, precisely, the results of applying the optimal CBM policy. In these tables, the saving expected results are:

- **At (20 rpm, 20 Nm), Table 3**

1. In the healthy gearbox, the maintenance cost (L.E./hr) saving is the maintenance cost (L.E./hr) 50.7% with total maintenance cost saving (L.E.) of 83.38%. (filtered signal). On the other hand, the operating time between failure and optimum (hr) saving is worse by 67.72% (filtered signal). In the case of the main bearing inner race crack, the maintenance cost (L.E./hr) saving is the maintenance cost (L.E./hr) 51.74% with total maintenance cost saving (L.E.) of 83.68% (filtered signal) . On the other hand, the operating time between failure and optimum (hr) saving is worse by 66.66% (filtered signal).

2. The availability saving is the availability -26.4% (filtered signal). On the other hand, the operating time between failure and optimum (hr) savings are worse by 60.56% (filtered signal). In the case of the main bearing inner race crack, the availability savings is the availability -45.15% (filtered signal). On the other hand, the operating time between failure and optimum (hr) saving ls worse by 59.58% (filtered signal).

3. The maintenance cost and availability (L.E./hr) saving is the maintenance cost and availability (L.E./hr) 49.3% with total maintenance cost and availability saving (L.E.) of 86.9% (filtered signal) . On the other hand, the operating time between failure and optimum (hr) savings is worse by 75.91% (filtered signal). In the case of the main bearing inner race crack, the maintenance cost and availability (L.E./hr) saving is the maintenance cost and availability (L.E./hr) 51.11% with total maintenance cost and availability saving (L.E.) of 83.70 (filtered signal) . On the other hand, the operating time between failure and optimum (hr) saving is worse by 66.66% (filtered signal).

- **At (40 rpm, 40 Nm), Table 4**

1. The maintenance cost (L.E./hr) saving is 50.7% with total maintenance cost saving (L.E.) of 83.9% (filtered signal). On the other hand, the operating time between failure and optimum (hr) saving is worse by 67.33% (filtered signal). In the case of the main bearing inner race crack, the maintenance cost (L.E./hr) saving is 55.37% with total maintenance cost (L.E.) saving of 88.84% (filtered signal) . On the other hand, the operating time between failure and optimum (hr) savings are worse by 75.00% (filtered signal).

2. The availability saving is -30.3% (filtered signal). On the other hand, the operating time between failure and optimum (hr) saving is worse 60.85% (filtered signal). In the case of the main bearing inner race crack, the availability saving is -34.58% (filtered signal). On the other hand, the operating time between failure and optimum (hr) saving is worse by 65.00% (filtered signal).

3. The maintenance cost and availability (L.E./hr) saving is 45.9% with total maintenance cost and availability saving (L.E.) of 86.3% (filtered signal). On the other hand, the operating time between failure and optimum (hr) saving is worse by 74.90% (filtered signal). In the case of the main bearing inner race crack, the maintenance cost and availability (L.E./hr) saving is 51.06% with total maintenance cost and availability saving (L.E.) of 87.77% (filtered signal). On the other hand, the operating time between failure and optimum (hr) saving is worse by 75.00% (filtered signal).

The same discussion can be applied on the rest of the wind turbine planetary gearbox components faults considered.

6.2. Gearbox Components Cost Saving Assessment

The preventive replacement is one of the effective strategies to reduce the probability of failure (reduce failure cost) and downtime (reduce production losses) in the deteriorate condition. Furthermore, preventive replacement is the most appropriate maintenance strategy for component which operates in the stage of fault life. From the previous discussion, the per cent savings of total cost, availability and total cost and availability estimated based on filtered signal for all wind turbine components considered in this work are used in prognostic process and are shown in Figure 15 to Figure 17 at speed 20 rpm, 20 Nm and speed 40 rpm, 40 Nm respectively. However, these per cent saving values are used to evaluate the wind turbine gearbox components cost saving assessment. Furthermore, these figures also depict the influence of speed-load torque on the per cent savings of total cost, availability and total cost and availability for the wind turbine gearbox components. It is observed that the per cent savings at 40 rpm, 40 Nm are higher than those estimated at 20 rpm, 20 Nm for filtered signal. It is recommended that the determination of the per cent saving of total cost for any component should be done at high speed-torque load (power) conditions. In Figure 18, comparison between per cent of total cost savings without availability and total cost with availability at 20 rpm, 20 Nm and 40 rpm, 40 Nm for filtered signals for all the wind turbine components considered in this work. Generally speaking, the estimated per cent savings of total cost and availability are higher than those for the cost without availability. This is due to the consideration of availability into account when dealing with total cost estimation, where the imperfect maintenance actions and the short-run availability constraint are considered. Bearing in mined that the proposed approach which integrates the continuous monitoring and the determination of the preventive maintenance threshold is practical, robust and effective.

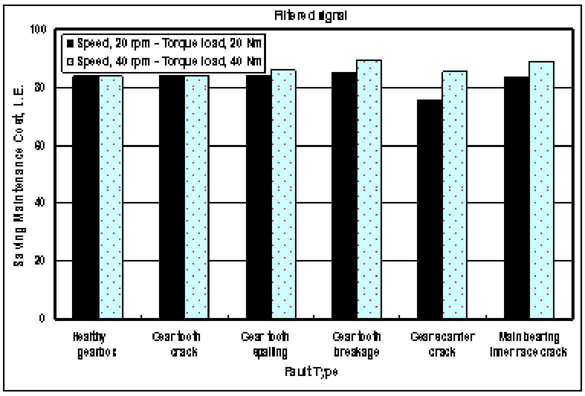

Figure 15. Saving total cost for gearbox components faults, filtered signal

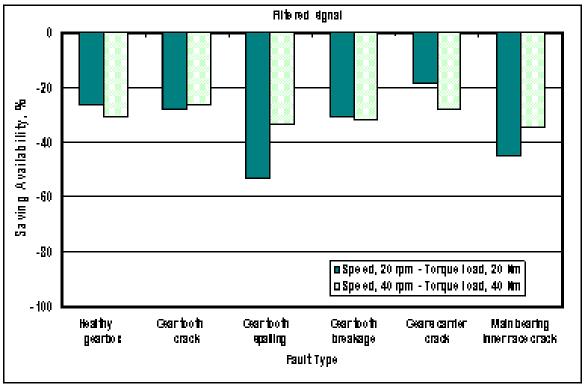

Figure 16. Saving availability for gearbox components faults, filtered signal

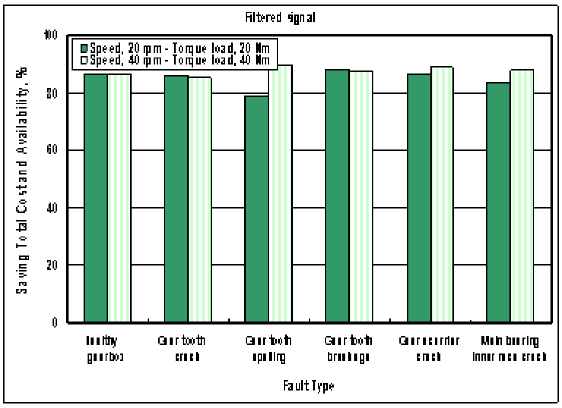

Figure 17. Saving total cost and availability for gearbox components faults, filtered signal

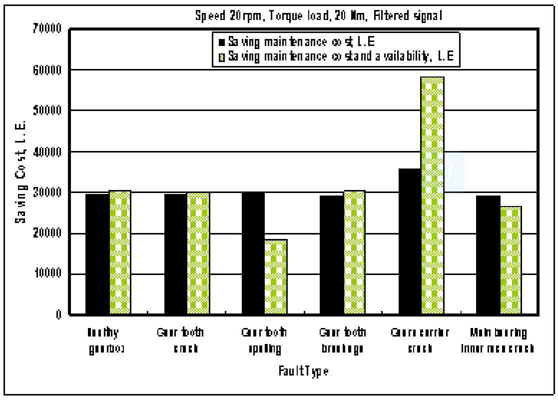

Figure 18. Comparison between total cost, and total cost and availability for gearbox components faults for measured signal at 40 rpm, 40 Nm

Table 5. Change of per cent saving total cost, availability; and total cost and availability from the healthy gearbox (%)

No.	Speed – Torque load, (rpm- Nm)	Gear tooth Crack	Gear Tooth Spalling	Gear tooth Breakage	Gears Carrier Crack	Main Bearing inner race Crack
	Saving total cost per unit time change from the healthy gearbox , %					
1	20 rpm – 20 Nm	0.036	0.50	1.90	9.96	0.14
2	40 rpm – 40 Nm	0.39	2.44	6.98	2.22	5.88
	Saving availability change from the healthy gearbox , %					
3	20 rpm – 20 Nm	4.36	102.20	16.33	30.19	71.02
4	40 rpm – 40 Nm	12.70	10.33	4.69	8.35	14.13
	Saving total cost and availability per unit time change from the healthy gearbox, %					
5	20 rpm – 20 Nm	1.08	40.38	0.811	90.74	12.29
6	40 rpm – 40 Nm	0.44	4.77	35.05	19.37	2.68

Table 5 tabulates in percentage of the change from the healthy gearbox (CFHL) of the per cent savings total cost, availability and total cost with availability for all the wind turbine components considered in this work**.** The speed-load torques are being 20 rpm, 20 Nm and 40 rpm, 40 Nm for filtered signals. From the previous discussion, it is stated that the highest per cent savings obtained are from the total cost and availability. Based on the CFHL in the tables and for the total cost and availability, the planet gears carrier crack has the highest change from healthy gearbox followed by either planet gear tooth spalling or planet gear tooth breakage with either main bearing inner race crack or planet gear tooth crack has the least change.

7. Conclusion

1. Results are presented for cost analysis of wind turbine planetary gearbox components conditions using cost analysis models. The prognostic performance was illustrated using five types of gearbox faults. Maintenance managers can use the methods described herein as a practical way to improve the return on investment in their existing CBM programs. The sample size of the data (number of histories, not number of inspections) analyzed in this sub-task is relatively low. Although larger sample size would provide greater confidence, the test rig data was found to be adequate for demonstrating the usefulness of PHM and decision policy methodology described in this analysis for predicting and preventing gearbox failures.

2. The maintenance cost results of prognostic-based maintenance policy corresponding to different values of inspection cost. One can obtain an optimal solution under this maintenance policy. It is noted that all maintenance cost results converge to the optimal value of the age replacement policy which has the same configuration when inspection interval increases. This can be explained by the fact that the maintenance policy becomes close to the age replacement policy when inspection interval is large enough. The cost comparison generates the average

cost per unit operating calculated when the policy is applied retroactively to the data used in the analysis. Also, the results of the cost comparison are summarized.

3. The Cost Comparison function may be considered as a final check of the statistical and decision model by reporting whether the decision model is useful, i.e., whether it improves current practice. On the other hand, the cost savings associated with early detection of incipient failures are quantified. This will require better tracking of costs associated with various types of repairs, including repairs completed in the nacelle versus repairs done in a repair facility. Moreover, It is recommended that the determination of the per cent saving of total cost for any component should be done at high speed-torque load (power) conditions.

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