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Optimize the corrective maintenance technique of wind turbine

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ABSTRACT

Wind power is an important source of renewable energy. Operation and maintenance (O&M) costs account for 25-30% of the wind energy generation cost. A common goal of operation and maintenance optimization for a system is to decrease downtime, improve availability, and reduce the cost as much as possible.

In this thesis, we focus on the wind farm, which involves multiple wind turbines and each wind turbine is consisted of multiple turbine components. We propose several maintenance optimization models corresponding to corrective maintenance, and opportunity maintenance, respectively. (1) A corrective maintenance optimization model is proposed to optimize the number of failures allowed before performing corrective maintenance, and real wind turbine data are used in this study; (2) Opportunity maintenance methods are developed for wind farms to perform preventive maintenance actions when a failure occurs, Cost evaluation algorithms are developed for these proposed methods, and optimal maintenance strategies can be obtained via optimization.

Keywords: wind turbine; maintenance technique; optimization; ;

I. INTRODUCTION

Wind, like solar and hydroelectric, is an important natural source that is essentially inexhaustible. Very significant financial investments have been made in developing wind farms and the associated grid connection facilities all over the world. India has set its wind-generated energy output target to accounting for 55% of Renewable energy), India added a record 5400 Megawatts (MW) of wind power in 2016-17, exceeding its 4000 MW target. Currently, the India generated wind energy has increased to approximately 31 GW (28.7 GW) at the end of 2016 from 740 MW at the of 1997 with an average annual growth rate of 15 percent.

However, improving productivity of wind turbines and maximizing return on investment in wind farms requires maintenance strategy that is appropriate (technically feasible and economically viable) over the life-cycle of wind turbines; given that, “the net revenue from a wind farm is the revenue generated from sale of electricity less operation and maintenance (O&M) expenditure” ..

Wind turbines are usually purchased with a 2-5 years all-in-service contract, this include warranties and preventive and corrective maintenance, these are often adopted at the expiration of the contract period to maintain wind turbines. However unexpected equipment failures occur between Time Based Maintenance intervals thus manpower, time, and money are usually wasted on periodic maintenance with little knowledge of the current equipment condition. Moreover, Failure Based Maintenance can result to catastrophic critical components failure with severe operational, Health, Safety and Environmental (HSE) consequences. Hence, the adequacy of these technique to support the current commercial drivers of the wind industry is limited.

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Commonly used in many other industries, condition-based maintenance (CBM) is regarded by many studies as the most beneficial method due to the fact that it continuously monitors the performance of the wind turbine parts and determines the best time for a specific maintenance work. Therefore, the cost can be very much reduced without failure damage and high scheduled preventive maintenance workload, and the system reliability can be improved as well.

However, in CBM, reliable sensor providing accurate condition data will be required as any component of wind turbine system, especially under extreme environment condition and high load, in particular for offshore farms. Meanwhile, establishing the relationship between failure mode and observed data is also a big challenge. These could make operators interested more in failure-based maintenance (corrective maintenance), opportunity maintenance, and time-based maintenance (fixed interval preventive maintenance). Failure-based (corrective) maintenance is carried out only after a failure occurs. Time-based preventive maintenance is that the preventive maintenance is performed every after fixed interval of time. Opportunity Maintenance is a combined maintenance strategy, which is the preventive maintenance performed on certain running components by chance of a failure occurrence in a farm. In some cases CBM is not always cost-effective, and a study stated that scheduled inspection of the drive trains of wind turbines is more cost effective over life-cycle than CBM with almost 50% saving.

As discussed above, failure-based maintenance, opportunity maintenance and fixed interval maintenance deserve extensive study in case of wind projects, particularly those located at off shore wind farms where accessibility is weak and maintenance workload is heavy and very costly.

S. No.	Location (State wise)	Capacity In (KW)
1	Andhra Pradesh	1393.5
2	Gujarat	4030.65
3	Karnataka	2878.3
4	Kerela	43.4
5	Madhya Pradesh	2171.9
6	Maharashtra	4070.65
7	Rajasthan	3994.9
8	Tamil Nadu	7652.6
9	West Beangal	1.1
10	Telangana	77.5
11	Others	3.2
	Total	26915

Table 1.1: The existing wind farms in India listed by state at the end of march 2016

1.1 Objective of the Study

This project work focus on failure-based maintenance, opportunity maintenance and fixed-interval preventive maintenance, and performs comparative study of the benefits with different technique. The main objective is to give recommendations on the use and benefit of this maintenance technique in the Wind farm applications.

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We conclude that each maintenance strategy can be optimized, and the most economical maintenance strategy is found such that the average maintenance cost is the lowest. The main focus of this work is summarized as follows.

- We propose a corrective maintenance optimization model, in which a certain number of turbines are allowed to fail before the corrective maintenance is carried out. We also present an analytical method to accurately solve the optimization problem. The optimal number of failures is found such that the average maintenance cost per day is minimized.
- We have considered an offshore wind farm and their maintenance techniques. Under the current scope we have used failure-based maintenance, opportunity maintenance and fixed-interval preventive maintenance and based on the condition of component in opportunity maintenance technique.

II .FUNDAMENTAL TERMS

2.1 Reliability Theory

The term Reliability can be applied to various human activities as well as the performance of physical systems or functional objects. The objects can vary with terms “unit”, “component”, “equipment”, “item” and “system” as appropriate throughout this paper. To focus on functional objects, the definition of reliability is: the probability that an item will perform its intended function for a specified interval of time under stated conditions.

2.2 Maintenance and Optimization

Maintenance is categorized into failure-based, time-based, and condition-based maintenance.

Failure-based (corrective) maintenance is carried out only after a failure of item occurs. It aims at return the item to functional state, either by repairing or replacing action.

Time-based (scheduled) maintenance is carried out after a pre-scheduled interval no matter the failure occurs or not. This strategy can be classified into fix-interval based and age-based maintenance.

Maintenance Condition-based Time-based Preventive Maintenance Corrective Maintenance Condition-based maintenance is carried out when monitoring data signs the necessity of preventive maintenance. It will minimize the downtime and repair costs since the prediction of remaining time of components is more precise, .However, CBM is not mature for wind turbine systems. The sensors should be reliable to present the state of component precisely. Furthermore, the knowledge of the relationship between failure mode and monitoring data is still a challenge, we summarize the advantages and disadvantages of these general maintenance technique in the wind power industry as below

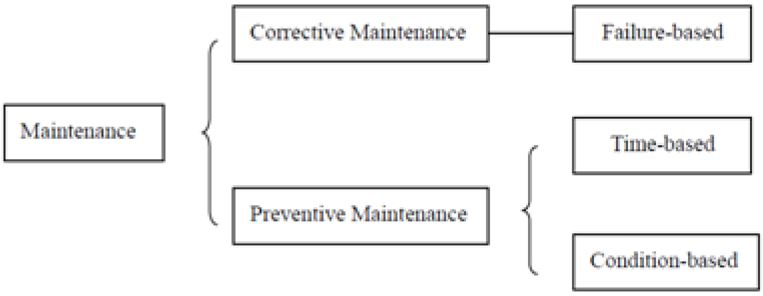

Figure 2.1 Maintenance Classification

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Corrective maintenance

- Advantages

  ---- Components will be used for a maximum lifetime;

  ---- Lower investment on monitoring component.

- Disadvantages

  ---- High risk in catastrophic damage and long down time;

  ---- Spare parts and logistics allocation is complicated;

  ---- Likely long lead time for repair.

Time-based preventive maintenance

- Advantages

  ---- Easy logistics;

  ---- Shorter downtime and higher availability;

  ---- Maintenance activities can be well scheduled

- Disadvantages

  ---- Components won't be used for maximum lifetime;

  ---- Cumulative fixed cost is higher compared to corrective maintenance due to more frequent set out.

Condition-based preventive maintenance

- Advantages

  ---- Components will be used the most efficiently;

  ---- Maintenance activities can be well scheduled;

  ---- Downtime is low and availability is high;

- Disadvantages

  -----High investment and effort on reliable monitoring system;

  ---- Not a mature application in wind industry;

  ---- Difficult to identify appropriate condition threshold.

2.3 Maintenance Optimization:

Maintenance optimization is to determine the most cost effective maintenance strategy. It should provide the best balance between direct maintenance costs and the consequences of not performing maintenance as required. Obviously, more frequent maintenance activities result in more direct cost, thus the consequences of not performing maintenance activities decreases. In contrast, less frequent maintenance, lower cost but higher risk. Optimization deals with the interaction between these factors and aims to determine the optimum level. This is usually obtained at the best point on the key variable, where maintenance activities will bring the lowest total cost.

Figure 2.2 illustrates an optimization example by determining the optimal number of failures allowed to perform corrective maintenance, for which the minimum unit cost is obtained. This example illustrates the concept of our proposed corrective maintenance optimization model.

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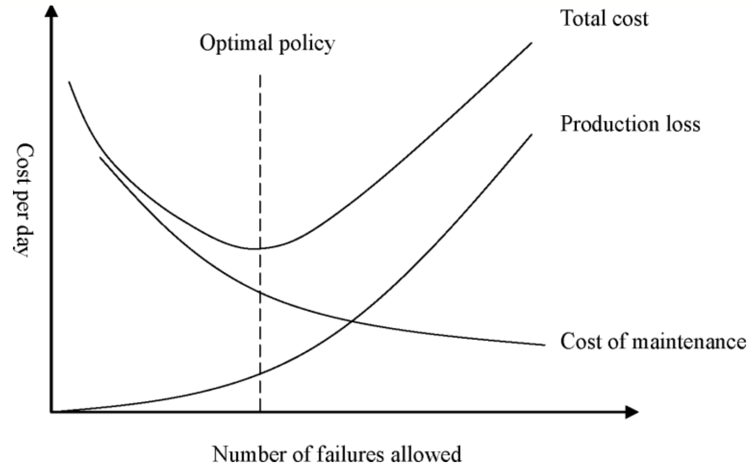

Figure 2.2 Optimal number of failures allowed

The objective of an optimal maintenance decision may be to minimize the total cost, or may be to maximize the availability of system, or profit and so on. In this thesis, we will focus on the cost optimization problem by determining an appropriate variable.

The main purpose of maintenance optimization for power plants is to determine the most cost-effective maintenance strategy, which will provide the best possible balance between direct maintenance costs, e.g. labor, resources, materials and administration costs, and anticipated income and profit. when considering the maintenance technique then three categories can be used known as the reliability centered maintenance, the total-productive maintenance and risk based maintenance

- Reliability centered maintenance**.** This technique is used to optimize the practices of the maintenance strategy in order to prevent the reliability level of the system from dropping below a certain specified value at any means. This approach is based on achieving a level of reliability for the items/parts required at any maintenance cost. This technique is employed for items/parts that are critical for the operation of the system, or their failure could result in catastrophic system failure or high loss of revenue.
- Total productive maintenance. This technique is a critical addition to lean production, where the maintenance tasks and operations are designed to achieve the desired goal, e.g. high production or low cost. This maintenance optimization is based on a combination of preventive maintenance actions and continuous efforts to modify and redesign equipment and techniques with a goal to increase flexibility in processes and promote higher yield in production.
- Risk based maintenance**.** It aims at reducing the overall risk of failure of the operating facilities. In areas of high and medium risk, a focused maintenance effort is required, whereas in areas of low risk, the effort is minimized to reduce the total scope of work and cost of the maintenance program in a structured and justifiable way.

III. WIND TURBINE FAILURE DATA ANALYSIS

Wind turbine failures in an interval equals to the sum of component failures. The population difference of each interval can be eliminated by calculating the average failure rate with dividing by the corresponding number of turbines in that interval.

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As we collect data from a large population, we can get an average failure rate at a given interval. The failure rate is the number of failures per wind turbine per year, which can be obtained by dividing the total number of failures in a specific interval by the number of population for the interval and by the length in year of the interval.

$$\lambda_{i,k} = \frac{12\ n_{i,k}}{N_k}$$

Where is the No. of failure of component i in the interval k and is the total number of population in the interval k.

Table 3.1 xyz company turbine failure data

No. of Turbine Reporting 324	Failure rate (sep 2011- Aug 2012)
Entire unit	2
Rotor	2
Air brake	4
Mechanical brake	2
Pitch adjustment	6
Main shaft / Bearing	4
Gear box	3
Generator	2
Yaw system	3
Windvane /anemometer	3
Electronics control/system	3
Hydraulics	5
Sensor	4
other	2
Total	45

Similarly, the failure rate of a wind turbine system for the overall period, denoted by λ, is calculated as follow:

$$\lambda = \frac{\sum_k \sum_i\ 12\ n_{i,k}/N_k}{\sum_k T}$$

As a result, the failure rate λ of each component is shown in Table, and we get:

$$\lambda = 0.1388$$

The calculated average failure rate λ=0.1296 will be used to study corrective maintenance optimization in the following chapter. In case of a random failure pattern where the process follows exponential distribution, preventive replacement is not appropriate since such replacements do not lower component's failure rate.

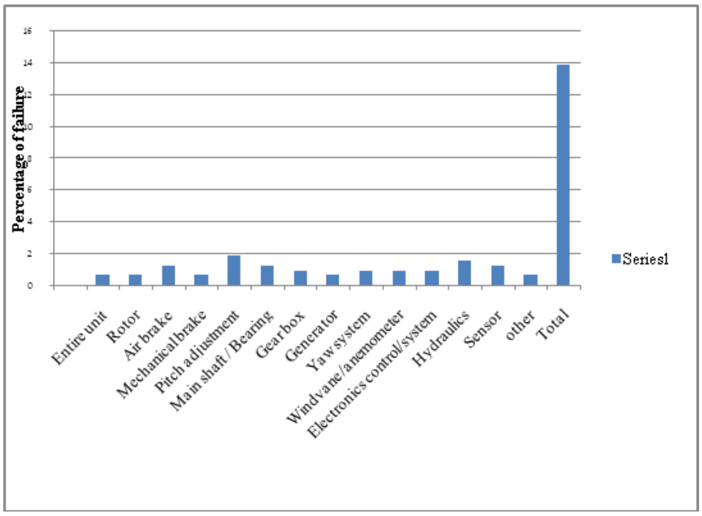

Figure 3.1 Xyz company turbine average failure rate

Component	**Average failure rate over (Sep.2011 – Aug 2012)**
Entire unit	0.6172
Rotor	0.6172
Air brake	1.234
Mechanical brake	0.6172
Pitch adjustment	1.851
Main shaft / Bearing	1.234
Gear box	0.925
Generator	0.617
Yaw system	0.926
Windvane /anemometer	0.926
Electronics control/system	0.926
Hydraulics	1.543
Sensor	1.234
other	0.6172
Total	13.88%

Table 3.2 Xyz company turbine average failure rate

IV. METHODOLOGY

CORRECTIVE MAINTENANCE

We discuss the corrective maintenance strategy for a remote wind farm, and construct an optimization model to make corrective maintenance more cost-effective. An approach is developed to solve the optimization problem. In application section, we use the simulation method to verify the mathematical approach.

4.1 Statement of the Problem

In a remote wind farm particularly an offshore farm, a maintenance task is expensive due to the complex on-site servicing work requiring heavy transportation and lifting equipment. In addition, the wind turbine systems are exposed to wind and other undesirable weather condition which makes access difficult. Therefore, a general question regarding the maintenance is arising, whether wind turbines are often in need of maintenance.

Thus, after manufacturers‟ certain warranty period, the owner may wish perform corrective maintenance only when a failure occurs. Nevertheless, a failure consequence is very large due to possible catastrophic damage caused by the failed component. Currently, studies on corrective maintenance for wind turbine systems are very few. Aiming at minimizing total operating and maintenance cost, there should be more efforts to make the study better. In this thesis, we study a corrective maintenance policy that allows multiple failures to occur before maintenance is carried out. With the comparison result, a useful recommendation in case of only performing corrective maintenance is presented.

4.2 Construction of Model

To focus on the topic study, we suppose a wind turbine system is consists of 4 key components, which are the rotor, the main bearing, the gearbox and the generator The model is based on the following assumptions or properties:

- The failures of components and turbine systems all follow exponential distribution.
- Any component failure will lead to turbine system failure, which means a wind turbine is a series system, and the simplified system structure is shown in Figure

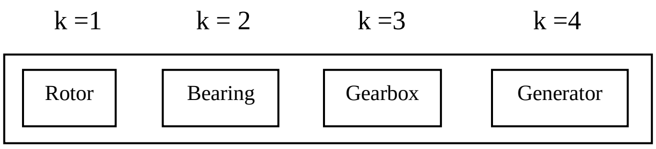

Figure 4.1 Series structure of a wind turbine

- Comparing to the component’s long lifetime, the replacement time is negligible.
- The failure-caused replacement cost is the sum of all direct cost, which not only considers material, but labor cost, transportation cost, loading and offloading cost, access cost, etc.
- The maintenance policy is to implement corrective maintenance only, where a certain number of wind turbines are allowed to fail before replacements are carried out. The objective is to determine the optimal number of failures allowed, denoted by , to minimize the total expected cost per day, which consists of replacement cost and production loss that a turbine out of service.
- Some of the notations are defined as follows:

  t_n : One cycle determined by the nth failure.

  C_f : The failure replacement cost.

  P_L : The production loss per day if a turbine stops.

  C_{fix} : The fixed cost of sending a maintenance team to wind farm.

The total expected cost per unit time per turbine for one cycle t_n denoted by $C(t_n)$, is

$$C(t_n) = \frac{Total\ expected\ cost\ per\ cycle}{Expected\ cycle\ length}$$

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Expected cycle length $t_n =$ mean time to nth failure, denoted by MTTF_n

Total expected cost per cycle

= replacement cost + fixed cost + production loss of turbine out of service

$= n \times C_f + C_{fix} + \sum_{i=1}^{n}(\mathrm{MTTF}_n - \mathrm{MTTF}_i) \times P_L$

The term "$\mathrm{MTTF}_n - \mathrm{MTTF}_i$ " is the duration that a system is out of service owing to ith failure it corresponds to. Fox example, a system fails first in the farm, then the expected failure time is the mean time to 1th failure, denoted by MTTF_1. If the corrective maintenance occurs at the time of nth failure, MTTF_n , the total stopped time of this system equals to $\mathrm{MTTF}_n - \mathrm{MTTF}_1$, and the total production will lose the amount of $(\mathrm{MTTF}_n - \mathrm{MTTF}_i) \times P_L$.

Therefore,

$$C(t_n) = \frac{n \times C_f + C_{fix} + \sum_{i=1}^{n}(\mathrm{MTTF}_n - \mathrm{MTTF}_i) \times P_L}{\mathrm{MTTF}_n} \qquad (4\text{-}1)$$

To solve the optimization problem we need to find MTTF_n first.

4.3 Find the Cycle Length MTTF_n

Suppose n =3, the procedure for the cycle length computation is give as follows

Step1. The failure probability density for a single component which follows exponential distribution can be written as below:

$$f(t) = \lambda e^{-\lambda t} \qquad (4\text{-}2)$$

Thus the probability that a 3rd failure in a group of N components occurs in $\{t + dt\}$, which is denoted by $f_3(t)$ is:

$$f_3(t) = \mathrm{P}(\text{2 failure occur before t}) \times \mathrm{P}(\text{1 failure occur in } \{t + dt\}) \times \mathrm{P}(\text{N} - \text{3 failureoccur after t})$$

$$= N \times C_{N-1^2} \times [F(t)]^2 \times f(t) \times [R(t)]^{N-3}$$

$$= NC_{N-1^2}(1 - e^{-\lambda t})^2 \lambda e^{-(N-2)\lambda t} \qquad (4\text{-}3)$$

Where N is the number of possible choices of finding one component which fail in $\{t + dt\}$. C_{N-1^2} is the number of possible choices of finding two component which fail before t.

Step2. The general mean time to failure can be derived by

$$MTTF = \int_0^{\infty} tf(t)dt \qquad (4\text{-}4)$$

Note that the probability that the 3rd failure happens in [0, ∞] is unity:

$$\int_0^{\infty} f_3(t)dt = 1 \qquad (4\text{-}5)$$

Substitute (5-3) into Equation (5-4), and solve the integral to get the MTTF_3, which is the length of cycle that every 3 failures occur.

Thus, we have

$$\mathrm{MTTF}_3 = \frac{3N^2 - 6N + 2}{\lambda N(N-1)(N-2)} \qquad (4\text{-}6)$$

This formula can also be derived easily by the sum of the mean time of the first failure for N components, the mean time of the first failure for N-1 components, and the mean time of the first failure for N-2 components

$$\mathrm{MTTF}_3 = \frac{1}{\lambda N} + \frac{1}{\lambda(N-1)} + \frac{1}{\lambda(N-2)} \qquad (4\text{-}7)$$

Now consider the general case, the expected time to the nth failure can be calculated as:

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$$\mathrm{MTTF}_3 \qquad (4\text{-}8)$$

Based on the above analysis, is the function of n, which can be appropriately denoted by C(n) ,becomes the design variable. Therefore, the objective function of proposed corrective maintenance optimization model can be briefly formulated as follows:

(4-9)

where C is the total expected maintenance per unit time per turbine.

4.4 Model analysis

4.4.1 Data

The method is applied to a wind farm with 50 2MW turbines. Each turbine consists of four key components: rotor, main bearing, gearbox and generator.

Failure distribution parameter

In previously we calculated the average failure rate of each component. Now consider the simplified four-component system. To reasonably specify the failure rate values, we need convert their failure rate based on the component's failure contribution to the whole system, so that the failure rate of turbine system is in accordance with the result of λ=0.1388

For example, in Previously, we calculate the real failure rates of these 4 components are: rotor 0.617%, Main bearing 1.234%, Gearbox 0.925%, Generator 0.617%. Thus, the failure rate of rotor regarding the simplified system with λ=0.1384 is given by:

$$\lambda = \frac{0.617}{0.617 + 1.234 + 0.925 + 0.617} = 2.52\%$$

The converted failure rates of four components are:

$$\lambda = 2.52 \qquad \lambda = 5.04 \qquad \lambda = 3.78 \qquad \lambda = 2.52$$

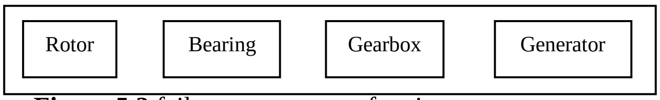

Figure 5.2 failure percentage of major component

Cost data

The production loss per day is calculated by :

$$P_L = 24\ hrs \times WT_{PR} \times C_E \times Cf \qquad (4\text{-}10)$$

Where, WT_{PR} is wind power rating, here $WT_{PR} =$ 2MWh. C_E is the cost of energy, C_E= 2700/- , Cf is capacity factor, here we suppose $Cf = 30\ \%$.

Based on component's failure replacement costs and their failure rates, the expected failure replacement cost Cf of wind turbine is then estimated as:

$$Cf = \frac{C_{Rotor} \times \lambda_{Rotor}}{\lambda_{WT}} + \frac{C_{Bearing} \times \lambda_{Bearing}}{\lambda_{WT}} + \frac{C_{Gear\ box} \times \lambda_{Gear\ box}}{\lambda_{WT}} + \frac{C_{Generator} \times \lambda_{Generator}}{\lambda_{WT}}$$

$$= 6048 \times \frac{2.52}{13.88} + 3240 \times \frac{5.04}{13.88} + 8208 \times \frac{3.78}{13.88} + 5400 \times \frac{2.56}{13.88}$$

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$= 5497.37/-$ (in **k**)

Component	Failure Replacement cost (Rupees in k)	Fixed cost to wind farm (Rupees in k)	Production Loss (Rupees in k)
Rotor	6048	2700	43200
Main Bearing	3240		
Gear box	8208		
Generator	5400		

Table 4.1 Cost data

4.4.2 Assessing Cycle Length by Simulation

Simulation is a very useful tool to solve nonlinear and complex problems. The higher

Step1: Simulation Initialization. Specify the maximum simulation iterations I As we mentioned earlier, there are 50 (m = 1,…………50) turbines considered in the wind farm, and 4 (k =1,...,4) components are considered for each turbine. The absolute time, , is defined as the accumulative time of every failure for that component. Obviously, at the beginning, =0 for all *k* and *m*. Generate the failure times for each component in each turbine by sampling the exponential distribution for component k with parameter The failure time of each component is represented byand at the time of first failure for all components.

Step 2: Recording the time to nth failure, and updating component absolute time and failure time value. The replacement decisions can be made according to the policy, described in Section 5.2, based on the comparison of absolute time Comparing the value of of all the component's, the nth small value implies the time of the nth failure, and the replacements are to be performed on all n components. Save this absolute time as the moment of the nth failure in the current simulation iteration, which is represented by. Regenerate new failure times for these replaced components, and the change in their absolute times is:

$$TA_{km} = t_i + TL_{km}$$

The time to nth failure of the Ith iteration, denoted by is given as:

$$\Delta t_i = t_i - t_{i-1}$$

Note that the functional components will stop working when there is failure occurring in their system. They will continue their remaining life after the replacement of the failed component. Thus, the change in their absolute times is:

$$TA_{km} = t_i + remaining\ life$$

If the current number of iterations has not exceeded the maximum simulation iterations I,

We will move to the next iteration:

$$\text{i} = \text{i} + 1$$

Repeat step2.

Step 3: Mean time to the nth failure calculation. When the maximum simulation iterations is reached, that is,,

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the simulation process is completed. We have:=**Δ**

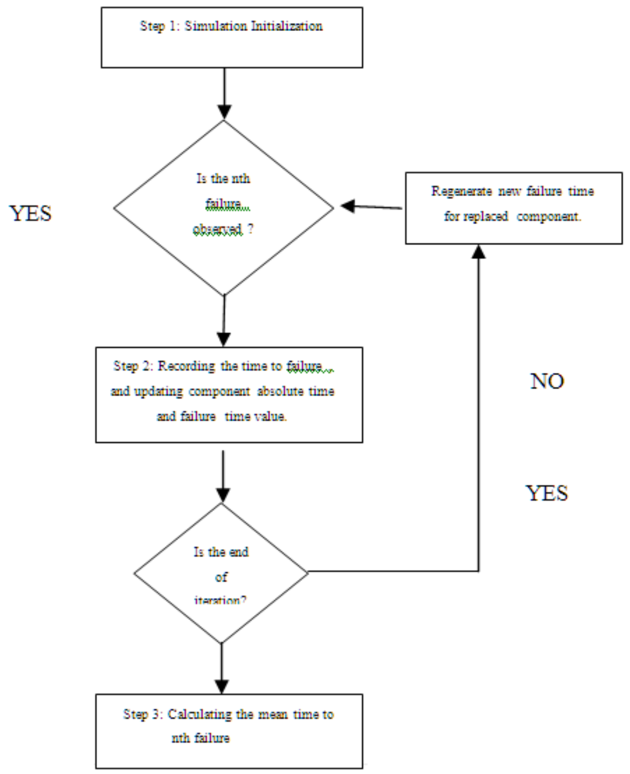

Figure 4.3 Flow chart of simulation process for evalution

Figure shows the obtained with simulation and the analytical method in Equation (5-8) respectively for a wind farm with 50 turbines. It can be seen that the result obtained using the simulation method and the analytical method agrees with each other.

Table 4.2 MTTF value

N =50 λ =13.88%

n	Simulation	Analytical
1	0.1406	0.1445
2	0.2965	0.292
3	0.4468	0.4425
4	0.5975	0.5962
5	0.7559	0.7533
6	0.9181	0.9139
7	1.0648	1.0781
8	1.2684	1.2461
9	1.4308	1.4182
10	1.5792	1.5944

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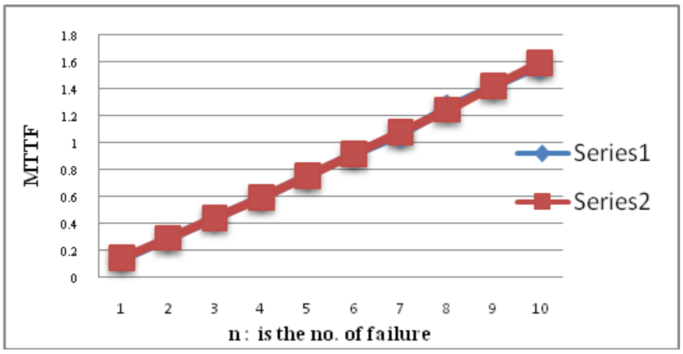

Figure 4.4 Simulation vs. Analytical result for

4.4.3 Cost Evaluations and Optimization Results

Using Equation (4-1) we obtained in Section 4.2, we calculate the expected costs corresponding to different number of failures allowed, then determine the optimal number of failures and cost. The result is presented in Figure 11.

We can find that the optimal failure number is 2, which corresponds to minimum total cost of Rupees 3383.64/day/turbine (in k). Even if the failure consequence is significantly large, the optimization result suggests that the owner of wind farm could get benefits by performing replacement after every 2 failures if only corrective maintenance strategy is considered.

Comparing with the cost of "replace after 1 failure", the cost savings using the proposed method is 3.5%.

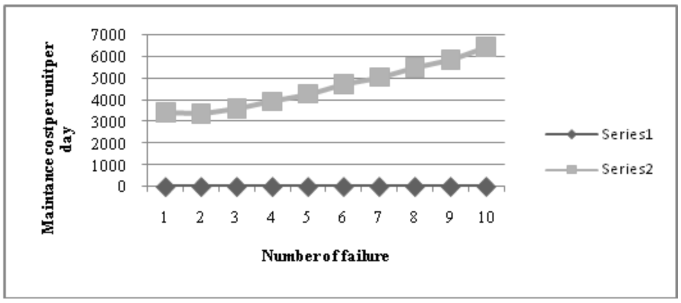

Figure 4.5 Cost vs. number of failure allowed (corrective maintenance)

V. CONCLUSION AND FUTURE WORK

5.1 Conclusions

Maintenance optimization creates outstanding benefits for many industries. However, it is relatively new for wind power industry, which has been growing very fast in recent years due to the highly increasing requirements on clean and renewable energy in human life.

In this paper, we focus on the wind farm, which involves multiple wind turbines and each wind turbine is consisted of multiple turbine components. We propose maintenance optimization models corresponding to corrective maintenance, methods are developed for wind farms to perform preventive maintenance actions when a failure occurs. Cost evaluation algorithms are developed for these proposed methods, and optimal maintenance technique can be obtained via optimization.

The proposed methods are demonstrated and compared. According to this the optimized corrective maintenance We can find that the optimal failure number is 2, which corresponds to minimum total cost of Rupees

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3383.64/day/turbine (in k). The developed methods in this thesis can be applied to improve the current maintenance practice in wind farms, and bring immediate benefits to wind energy industry in terms of reducing cost and improving availability.

5.2 Future work

Our first future work is to find analytical methods, which are more efficient for maintenance cost evaluation in the corrective maintenance optimization problems.

We can also extend the optimization study by considering additional variables and optimizing these variables. And compare them of optimum one.

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