

Maintenance Alternatives Related to Costs of Wind Turbines Using Finite State Markov Model

Boukelkoul Lahcen

Abstract—The cumulative costs for O&M may represent as much as 65%-90% of the turbine's investment cost. Nowadays the cost effectiveness concept becomes a decision-making and technology evaluation metric. The cost of energy metric accounts for the effect replacement cost and unscheduled maintenance cost parameters. One key of the proposed approach is the idea of maintaining the WTs which can be captured via use of a finite state Markov chain. Such a model can be embedded within a probabilistic operation and maintenance simulation reflecting the action to be done. In this paper, an approach of estimating the cost of O&M is presented. The finite state Markov model is used for decision problems with number of determined periods (life cycle) to predict the cost according to various options of maintenance.

Keywords—Cost, finite state, Markov model, operation, maintenance.

I. INTRODUCTION

THE efforts to optimize the operation and maintenance (O&M) costs starts with understanding the current costs and the factors that affect the life cycle cost. The maintenance costs of a new turbine will be very low but, as the turbine ages, these costs will increase. Poor maintenance can result in defective output, unsafe working conditions and increased production costs due to repairs and excessive downtime. One way to reduce the cost of operation and production is to optimize utilization of maintenance resources. Anytime we fail to perform maintenance activities intended by the equipment's designer, the operating life of the equipment is shortened. Instead of waiting for a piece of equipment to fail (reactive maintenance), it is preferable to utilize preventive maintenance, predictive maintenance, or reliability centered maintenance. According to [1], scheduled maintenance is carried out usually twice a year, and there are 2.2 failures per turbine a year, which require major repair. It is noteworthy that maintenance is different from the repair activity which is performed on a failed equipment to improve its condition from the failed condition to an operable condition. Costs for scheduled maintenance are easy to predict, they are following the service contract. Any other cost category, especially, repairs can change significantly from year to year [2].

II. COST ESTIMATION

A. SANDIA Model

The cost of energy produced by a wind turbine can be

L. B. is with the department of Electrical Engineering University of 20th Aug. 1955 Skikda, Algeria (phone: 213-774565246; e-mail: l_boukel@yahoo.co.uk).

related to the incurred costs and the energy output of the turbine. The relation of the levelised:

$$\text{levelised cost} = \frac{\text{total cost}}{\text{annual utilized energy}} \quad (1)$$

The accepted COE calculation is given by the following relation [3]:

$$\text{COE} = \frac{\text{ICC} + \text{FCR} + \text{LRC}}{\text{AEP}_{\text{NET}}} + \text{OM} \quad (2)$$

$$\text{AEP}_{\text{NET}} = \text{AEP}_{\text{GROSS}} * \text{Availability} * (1 - \text{Losses}) \quad (3)$$

where, COE: Cost of Energy (\$/kWh), ICC: Initial Capital Cost (\$), FCR: Fixed Charge Rate (%/year), LRC: Levelized Replacement Cost (\$/year), OM: Operations and Maintenance Costs (\$/kWh), AEP: Annual Energy Production (kWh/year). In this relation, the operations and maintenance are assumed to scheduled, unscheduled and condition monitoring system. The separation is to indicate the difference between LRC and OM. LRC costs are related to major overhauls characterized by high downtimes and low frequency rate to failure. LRC is the responsibility of design department, while OM cost is directly affected by turbine availability, accessibility and supportability which are the responsibility of the operation and maintenance staff [4].

B. Modified NEA Model

$$\text{levelized cost} = \text{TC} / \sum_{t=1}^n \text{AUE}_t \cdot (1+r)^{-t} \quad (4)$$

$$\text{TC} = I + \sum_{t=1}^n (\text{OM}_t + \text{SC}_t + \text{RC}_t) \cdot (1+r)^{-t} - V(1+r)^{-n} \quad (5)$$

Equation (5) gives the discounted present value of total cost of the produced energy. TC, takes into account: the investment cost I, operation and maintenance cost OM_t , social cost SC_t , retrofit cost RC_t during year t and salvage value SV for n years.

$$\begin{aligned} \text{AUE}_t &= \text{ANE}_t \cdot k_{\text{los},t} \cdot k_{\text{util},t} \\ &= E_{\text{pot}} \cdot K_{\text{per},t} \cdot K_{\text{site},t} \cdot K_{\text{ava},t} \cdot K_{\text{los},t} \cdot K_{\text{util},t} \end{aligned} \quad (6)$$

AUE_t , the utilized energy during year t, is the annual potential energy output, E_{pot} , corrected by some factors due to different types of losses. These main correction factors are [4]: $K_{\text{los},t}$: Electric transmission losses, $K_{\text{util},t}$: Utilisation factor, $K_{\text{per},t}$: Performance factor (rain, dirt, etc.), $K_{\text{site},t}$: Site factor (obstacles), $K_{\text{ava},t}$: Technical availability factors (failure, service).

In order to minimize the total cost of the yield energy, optimization of maintenance is needed. That is to determine an

optimal maintenance strategy that is technically feasible and economically viable over the life cycle of physical assets. The strategy should provide the best possible balance between maintenance costs, risks involved, equipment reliability and availability without prejudice to safety and environment. Therefore, it is necessary to consider the strategic importance of quantitative maintenance optimization and proactively realize the benefits that are available through practical implementation of optimal maintenance strategies over the life cycle of the WTs.

C. Maintenance Strategies

Common maintenance strategies applied to wind turbines include 'Time-Based' which involves carrying out maintenance tasks at predetermined regular-intervals and 'Failure-Based' which entails using a wind turbine until it fails [5]:

- Corrective Maintenance or run-to-failure defines a strategy that a system or a device operates until it fails. when it fails, the equipment is fixed without performing any scheduled maintenance. This strategy helps to avoid unnecessary repairs or inspection.
- The objective of preventive maintenance is to replace components and refurbish systems that have defined useful lives, usually much shorter than the projected life of the turbine. Tasks associated with scheduled maintenance fall into this category. PM reduces the amount of unplanned maintenance, but does this by increasing the amount of planned maintenance.
- Predictive maintenance the concept behind, is that maintenance should only be performed when a component is degrading, but before failure. It maximizes the service life of each component, reducing the cost of premature replacement, while at the same time eliminating the collateral damage that can occur if a component is allowed to run until it fails.

In wind farm operations, Reliability-centered Maintenance (RCM) is an advanced strategy used to optimize reliability, production, and asset life. RCM emphasizes the use of Predictive Testing and Inspection (PT&I) techniques in combination with traditional reactive, preventive, and proactive measures to determine the optimum tasks based on the consequences, costs, and safety risk. One key of the proposed approach is the idea of maintaining the WTs which can be captured via use of a finite state Markov chain. Such a model can be embedded within a probabilistic operation and maintenance simulation reflecting the action to be done.

III. MARKOV DECISION PROCESS

Suitable O&M models should be capable of evaluating the residual service life, the failure probability and the change of operational costs as a function of maintenance and renewal. A common objective of these models is to find the maintenance and renewal strategy where the total costs of repairs, inspections, production losses and other consequences are minimal. Based on Markov chains, a policy of maintenance options is derived according to the related costs is developed.

Markov decision processes (MDPs) (also known as stochastic dynamic programs) are an appropriate and utilized technique for maintenance decisions [7].

According to management strategies, many kinds of maintenance policy can be applied: preventive or corrective. As mentioned in the preventive maintenance, three scenarios of maintenance could be planned: no action which is the baseline scenario. The second scenario would be inspections. If the inspection reveals a defect, it orders a new component and repair/replace it. In the third scenario, condition monitoring system assumed to detect 90% of gearbox and generator defects. The transition probabilities, for one period, from one maintenance state to another state can be represented by the following transition matrix:

$$P^1 = \begin{matrix} & \begin{matrix} \text{next period} \\ 1 & 2 & 3 \end{matrix} \\ \begin{matrix} \text{actual period} \\ 1 \\ 2 \\ 3 \end{matrix} & \begin{bmatrix} p_{11}^1 & p_{12}^1 & p_{13}^1 \\ p_{21}^1 & p_{22}^1 & p_{23}^1 \\ p_{31}^1 & p_{32}^1 & p_{33}^1 \end{bmatrix} \end{matrix} \quad (7)$$

In P^1 the column represents the probabilities of the actions taken in actual period, while, the row defines the probabilities of next period actions.

The correspondence between the states and the decisions is as:

TABLE I
CORRESPONDENCE BETWEEN STATES AND DECISIONS

System's state	Decision made
1	baseline
2	inspection
3	Condition monitoring system

Since the management has the options to decide which scenario of maintenance must be done, it is expected, the cost will vary upon decision. Given the state of the system and the chosen action, an immediate cost is applied. No matter how good the design of turbine assemblies is, the turbine deteriorates overtime since it operates under environment involving randomness. The cost overtime will increase and the decisions will vary also with time. In this study, P^1 can have different values and so the associated rewards. R^1 and R^k are the cost (immediate rewards) associated with the matrices P^1 and P^k respectively.

$$P^k = \llbracket p_{ij}^k \rrbracket = \begin{bmatrix} p_{11}^k & p_{12}^k & p_{13}^k \\ p_{21}^k & p_{22}^k & p_{23}^k \\ p_{31}^k & p_{32}^k & p_{33}^k \end{bmatrix}$$

The corresponding rewards matrices are:

$$R^1 = \llbracket r_{ij}^1 \rrbracket = \begin{bmatrix} r_{11}^1 & r_{12}^1 & r_{13}^1 \\ r_{21}^1 & r_{22}^1 & r_{23}^1 \\ r_{31}^1 & r_{32}^1 & r_{33}^1 \end{bmatrix}$$

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The maintenance can be modeled as a finite state dynamic model. The expression governing this model is a recursive equation and is written as [8]:

$$f_n(i) = \min_k \{v_i^k + \sum_{j=1}^m p_{ij}^k f_{n+1}(j)\}, n = 1, 2, \dots, N - 1 \quad (8)$$

where, $k=1, 2 \dots$ the maintenance actions taken by the management, $m=3$, the number of states at each period. N is the number of periods. $f_n(i)$ is the optimal expected cost at periods n , and i is the state of the system at the beginning of year n . $v_i^k = \sum_{j=1}^m p_{ij}^k r_{ij}^k$ is the one step transition cost for the alternative k and the state i .

Due to recursive nature of (8), the values of $f_n(i)$ are determined by iteration (backward induction solution technique). Optimal solution is obtained by choosing the minimal/maximum cost related to the maintenance type considered for one period. Starting with a prescribed budget, what alternative of maintenance option to take can be decided. The probabilities of the decisions are taken upon statistical data from sites and research in the area [2], [6].

As a numerical example, a five period's maintenance is calculated to show the cost related to the alternatives taken by the management.

From Tables II-IV it is obvious that inspection is more economic (minimum cost) and would be the best option for maintenance. In Fig. 1, a comparison of costs related to three

maintenance options is shown. The probabilities of the options and corresponding costs are taken from LI M&R cost forecast [1]. The costs estimation is based on the assumption that the turbine is safe from severe failures (safe gearbox and generator). Monte Carlo method is used to generate the probabilities of maintenance alternatives. The periods taken are assumed to be every three years and ignoring the retrofit costs.

TABLE II
RESULTS FOR FIRST PERIOD

i	$v_i^k(i)$			Optimal solution	
	k = 1	k = 2	k = 3	$f_5(i)$	k^*
1	470	210	300	210	2
2	400	260	360	260	2
3	325	330	210	210	3

TABLE III
RESULTS FOR SECOND PERIOD

i	$f_n(i)$			Optimal solution	
	k = 1	k = 2	k = 3	$f_4(i)$	k^*
1	863	601	658	601	2
2	758	667	746	667	2
3	690	688	617	617	3

TABLE IV
RESULTS FOR FIFTH PERIOD

i	$f_n(i) * 1.0e + 3$			Optimal solution	
	k = 1	k = 2	k = 3	$f_1(i)$	k^*
1	1.8467	1.5099	1.5917	1.5099	2
2	1.6917	1.5786	1.6122	1.5786	2
3	1.5877	1.6217	1.5286	1.5286	3

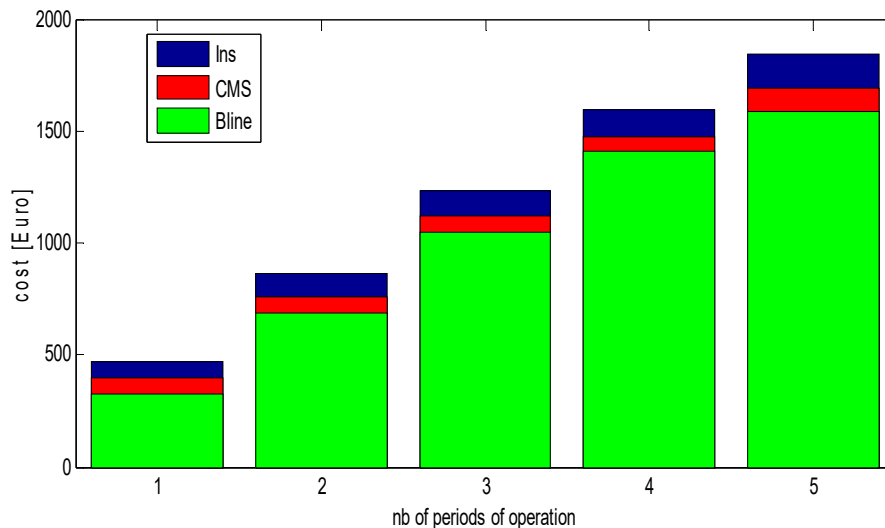


Fig. 1 Cost distribution for five periods of operation

IV. CONCLUSIONS

Maintenance policies have been chosen either on the basis of long-time experience or by following the recommendations of manuals issued by manufacturers. In both cases, maintenance has been carried out at regular, fixed intervals.

This practice is also called scheduled maintenance and, to this day, this is the maintenance policy most frequently used by electric utilities. Choosing between different options of maintenance and taking into account the economical aspect, it is necessary to balance in between. Markov decision process is a very useful technique for making a sequence of interrelated

decisions (O&M and economy). In this paper, the results have shown that inspection option is optimal. However, the constraints in this problem relate to the permissible changes in the component costs, probability and duration vectors. Thus, there are lower and upper limits on the amount of money available for maintenance and minimum and maximum times between inspections. Our study is limited for five periods equivalent to 15 years of operation with random probabilities of decisions made. This method can be implemented easily in practice (limited periods). Further studies may be carried with statistical information and so the results obtained will be consistent.

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