Reliability-based Maintenance Planning Methods in Power Industry: A Review

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Abstract

The service interruption in power industry can be unsustainable for most of the customers due to the wide range of the possible negative consequences. Therefore maintenance planning is critical in this industry and especially when it comes to the tradeoff between cost and reliability. Traditional maintenance strategies such as corrective and preventive maintenance have become inefficient to cope with the new industry challenges in term of cost and quality. Reliability Centered Maintenance (RCM) is one of the maintenance planning method that has been applied in both discrete and process industries. This paper demonstrates some methods of applying RCM in power industry their economic and quality impact on the maintenance strategy.

Keywords: *Reliability Centered Maintenance (RCM), power plants, mathematical models, repair/replace decision.*

I. INTRODUCTION

Because of their associated high risk during operations and the due to the new market challenges, corrective and pure preventive maintenance in industrial plants have become inadequate as maintenance strategy[1]. Therefore, an approach called Reliability Centered Maintenance (RCM) has been introduced by North American civil aviation industry in 1960s [2]that integrates corrective, preventive and proactive maintenance as a technique to increase the system reliability, [3].RCM has been used mainlyto reduce the maintenance cost by reducing the inadequate maintenance plans without affecting the quality of the system especially in highly automated plans with difficult-to-access locations[4]. In addition to cost mitigation RCM can be a tool to increase system reliability, safety [5] and security [6].

The main issue in maintenance strategy of electric power plan is avoiding service interruption [7] since this will cause a large variance of consequences on customers [6] since electricity is a very basic necessity in life and thus high reliability of power supply is always on demand [8, 9].Insuring continuous electric supply without interruption is costly and thus a creative maintenance planning is required. RCM is one of the tools that have been applied to power plants maintenance aiming totradeoff between the maintenance cost and reliability requirement, [10]. This paper demonstrates some of RCM applications in power industry.

II. MATHEMATICAL MODELS IN POWER PLANTS MAINTENANCE

Some of the mathematical models developed in maintaining electrical generators in power plants are summarized in this section, Perez-Canto and Rubio-Romero [7] developed a mathematical model to decide the preventive maintenance planof power generators in power plants that will maximize the reliability. The complexity of the problem lies in integrating all types of power plants installed in Spain in the study which are wind, hydroelectric, thermal and nuclear power plants. The objective is to maximize the reliability to satisfy the electricity consumption in Spain along with satisfying other economic and environmental constrains. For this purpose mixed integer linear programming was applied, and the objective was the reliability function defined as:

$$\text{Reliability}_{s,k,n} = P_s(\text{net power reserve}_{s,k,n}/\text{gross power reserve}_{s,k,n})$$

S refers to the electricity demand scenario (low, medium or high), K refers to the period (1 to 13), N refers to the subperiod in each period of time (1 to 6) and Ps refers to the probability of the scenario. Then the objective equation was subjected to 16 constraints. The most important were; a maximum number of maintenance for each period, deadline to finish the maintenance, maintenance of precedent generators, generators that can't be maintained simultaneously, interval between two generators maintenance, overlap between two generators maintenance, maximum manpower, number of allowed maintenance processes that are based on the geographical location of the plant due to environmental concerns and others. The computer-solved model resulted in a reliability of approximately 61% and this indicates the probability that power supply in Spain will not be disrupted if all other constraints are satisfied. It is inferred that increasing the reliability of the same model can be achieved by sacrificing some of the constraints and this will entail some economical or environmental concerns. Therefore, the model can be improved by including costs in the objective function.

Reihani et al. [11] used a novel method called hybrid evolutionary algorithm for scheduling optimal maintenance plan for electric power generators. This method combines External Optimization (EO) method with GA to tackle maintenance scheduling problem (Fig.1). 80 individuals were included in this study and each one consists of 33 components. EO/GA model improves the individual fitness by changing the least fitness values of components of each individual. Upon reaching the maximum iteration or stable value for the objective function then the individual with the best fitness value is selected. Finally the maintenance schedule for the 33 components is formulated by assigning the outage week for each component.

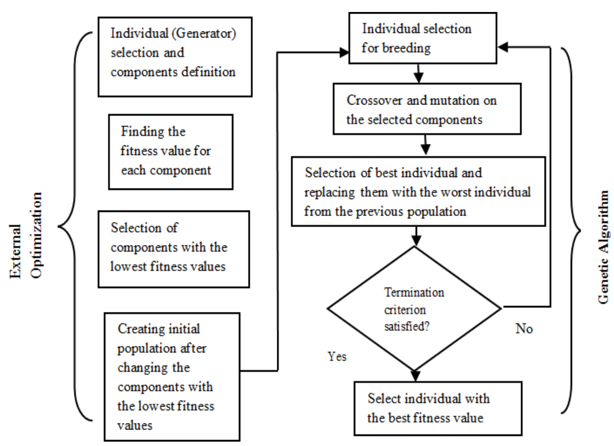

Fig.1: Evolutionary Algorithm for Scheduling Model [11].

III. MAINTENANCE OF ELECTRICAL TRANSMISSION AND DISTRIBUTION SYSTEMS

Heoet al.[12] applied RCM model for maintenance planning of the main electrical transmission components which are underground cables, overhead lines and insulators. Components state model was presented by modified Markov chains as shown in Fig.2. The state (N) refers to the new installed or repaired system, and then the state starts to deteriorate to subsequent degradation levels till failures. The reciprocal of the period between each transition referred as the transition rate (λ). The method (sensor) of determining the state is different from one component to another, measuring the isothermal relaxation used to determine the aging factor of the underground cable, line tension, temperature and line sag are considered for the overhead line and the insulator state is determined by the contamination severity.

The impact of a component failure in the transmission system is high since it affects other components in the system and thus the total maintenance cost of 30-bus system was included in the study. In order to find the optimal maintenance strategy a mathematical approach, Particle Swarm Optimization (PSO), was applied to RCM. By applying PSO two vectors assigned to every component; position and velocity. Then a fitness function is used to arrange the positions of the components base on the cost advantage. The duration of each component in its current state, transition rates (λ), repair times (μ) and maintenance cost of each state are inputted in the model. The fitness function in this model is iterated until the optimum cost over the specified life span is obtained by assigning numerical values for the states of each components measured by the methods mentioned earlier. The type of maintenance for each component was presented numerically with 0 (no maintenance required) up to 3 (stronger maintenance required). This mathematical model resulted finally in calculating the optimum cost for maintaining the whole 30-bus system by presenting the optimum maintenance strategy. The results were presented as the position number (2, 1, 2, …., 0, 0); the first number represents the maintenance scenario for the first component (strong maintenance), and second number represents the maintenance scenario for the second components (weak maintenance), and so on.

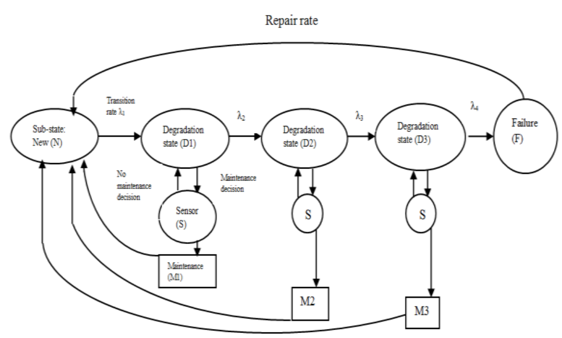

Fig.2: Components States Presentation using Semi-Markov Chain[10,12].

Kim et al. [10] have applied genetic algorithm to find the optimal maintenance strategy the will give the best cost advantage in electrical transmission system. The study was done on IEEE 9-bus and 118-bus systems for three components which are the overhead lines, insulators and towers. Semi-Markov chain (Fig.2) was used to present the components state model and the state criterion for the three components are shown in Table 1.

Table 1: The State Criterion of the Three Electrical Transmission Components [11].

<table>
<tr><th rowspan="2">State</th><th colspan="3">Overhead line</th><th colspan="2">Insulator</th><th colspan="2">Transmission tower</th></tr>
<tr><th>Tension</th><th>Temperature</th><th>Sag</th><th>The trace of the arc</th><th>The damaged spot</th><th>Erosion</th><th>Inclination</th></tr>
<tr><td>N</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="4">D1</td><td>0</td><td>0</td><td>X</td><td rowspan="2">0</td><td rowspan="2">X</td><td rowspan="2">0</td><td rowspan="2">X</td></tr>
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<tr><td>X</td><td>0</td><td>0</td></tr>
<tr><td rowspan="3">D2</td><td>0</td><td>X</td><td>X</td><td rowspan="3">X</td><td rowspan="3">X</td><td rowspan="3">X</td><td rowspan="3">X</td></tr>
<tr><td>X</td><td>0</td><td>X</td></tr>
<tr><td>X</td><td>X</td><td>0</td></tr>
<tr><td>D3</td><td>X</td><td>X</td><td>X</td><td colspan="4"></td></tr>
<tr><td>F</td><td colspan="7">Failure (out of service)</td></tr>
</table>

The fitness function in this model is evaluated in the following steps:

Constructing decision vector that represents the state of group of components (where 0 refers to N and 1, 2, and 3 refers to the deterioration state) by specifying the initial stage. Then the decision vector will be set to 1 in order to start iteration.

Failure pattern is estimated and then both the repair time and time to state is calculated.

The state of all components in the decision vector is then transited and the total cost then calculated.

The process of iteration will be kept until the life span is reached and the number of components in the decision vector reaches the total number of components in the system.

Base on the simulation results the optimal maintenance strategy that shows to the method and time of maintenance is then obtained. This model then was proven as cost-effective with comparison to the yearly preventive maintenance strategy.

Beehler[6] applied lighting analysis with RCM on a power transmission system for the purpose of making efficient maintenance planning to improve safety, security and reliability. The system components were defined by primary attributes such as; age, length of line segment, number of customers affected, total instantaneous outage and so on. And secondary attributes which are the soil characteristics, micro environment and structure standard. Engineering judgment was used then to weight these attributes and then formulating decision matrix that shows the assessment priorities. The lightning analysis (includes hazard analysis) then applied using computer software to the decision matrix and with the consideration of the secondary attributes, preventive maintenance plan for each components is then formulated base on the cost efficiency and failure mitigation. If there are components that have no cost efficiency for or high potential hazard upon failure then they will not be maintained and will be replaced upon their failure.

Yssaad et al. [13] have applied RCM in developing cost-effective maintenance strategy for electric power distribution system in Relizane, Algeria. The system that they were concerned with was the Electric Feeder System (EFS) and its dependent components due to its failure impact on most of the critical components in the system. The defined system components were: the electrical lines (EL), transformers (TR), circuit breakers (CB), insulator (IS), bus bar (BB), arresters (ARS) and fuses (FUS). The FMECA was applied to these components to come out the most critical components so that the focus then was limited to the components: EL, TR, CB and IS. Historical data were used to determine each component reliability and maintenance actions in addition to costs. By doing global optimization the optimum parameters of the whole system (λ, μ, A, R and M) were obtained and with application of two-parameter Weibull distribution graphical representations of these parameters were generated. The FMEA analysis with the quantitative results then utilized to establish a thorough maintenance plan. Comparison between the cost before the application of RCM and after showed the cost advantage of applying of maintenance plan base on RCM concept.

Gabbar et al. [2] have done a case study on nuclear power plant in which RCM was integrated with computerized maintenance management system (CMMS) in order to improve the maintenance strategy in term of cost-efficiency. The RCM function in the integrated system is performed by assessing the assets to be maintained base on their importance in the plant and performing failure analysis, decide the maintenance strategy and the associated costs, optimize the maintenance tasks and finally results checking and validation. Computer software (MAXIMO) was used for the optimization process and the RCM assessment methods were linked to the CMMS system architecture to decide the optimal maintenance plan. The maintenance plan formulated from the integrated system showed a reduction of about 16% of cost and 62% of downtime in comparison to the traditional preventive maintenance.

Väyrynen and Mattila [14] represented RCM model forwater hydraulic manipulator (WHMAN) which is a part from ITER (Internation Thermo-nuclear Experimental Reactor) remote handling.The model helps in increasing the plant availability by easing the maintenance management of the system. The reliability of the each component in WHMAN system was allocated individually either by testing or from supplier's data.Two maintenance schemes then were compared base on availability as a function of the system overhaul time and then the failure count and downtime for each individual component were presented graphically. With this information available the designer can specify which component has to bemostly improved in order to meet the system availabitlity requirements, moreover, these information can be used in establishing efficient maintenance plan.

IV. REPAIR/ REPLACE DECISION IN MAINTENANCE

The decision to repair or replace before failure require is vitally important especially when the cost of failure is higher than the cost of replacement of component before failure, [15]. Some studies that concerns about this topic in power industry are discussed in this section. Schlabbach and Berka [16] have used a qualitative analysis with simple quantitative means to take optimal repair/replace decision for 241 circuit breakers in electric power system. They have used two different indices; condition indices and importance indices. For the condition assessment includes the surrounding conditions, age, time since last maintenance, extinguishing medium and so on. The importance on the component refers to the potential loss of failure and the consequences on the whole system. The formula for calculating the importance is:

Importance index = failure rate (λ) × min. mean-time to repair/replace × (1+ scaling factor (power outage due to failure/maximum power supply by the component))

By doing a graphical representation for the two indices the repair/replace decision can be decided according the predefined limits as shown in Fig3.

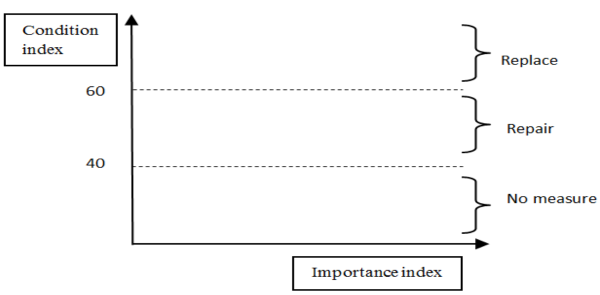

Fig.3: Repair/Replace Decision Graph [16].

Berrade et al. [17]used probabilistic mathematical model that reduces the chances of imperfect inspection that causes replacement of undefective parts and which leads to incurring unnecessary costs. The data were taken from a maintenance schedule of electric motors in trains where the overheated contactors are placed during every periodic inspection. Positive inspection means the part is defective, but this positive inspection could be false positive. Double inspection can solve this but will incur higher costs for the second inspection. Therefore, cost parameters in addition to inspection parameters (probabilities of false positive/negative inspections) were included in two-parameter Weibull distribution. The optimal maintenance policy was graphically presented as a function of cost. The components in this system are heterogeneous which means that it includes weak and strong components, and that creates a concern with the possibility that strong component is replaced by weak one and thus reducing the reliability of the system. Interestingly the optimal reliability in this study was found to be near the optimal cost strategy.

Marais [18] has considered the value of the system in formulating maintenance policy rather than just focusing on cost minimizing. He studied the optimal maintenance decisions (repair/replace) toward system components that insure the best value maximizing of the whole system. The virtual age in his study referred to the age in which the components must be replaced, and this age subjected to change (renew) after a repair process and it goes back to zero after replacement (Fig.4). A mathematical model called dynamic programming was used for the quantitative study which includes parameters of repair level, cost of new system, repair cost, operating cost and operating revenue. The optimal repair/replace decision in the system was presented with regard to several variations of the parameters such as; time horizon, repair level, operating profit and so on.

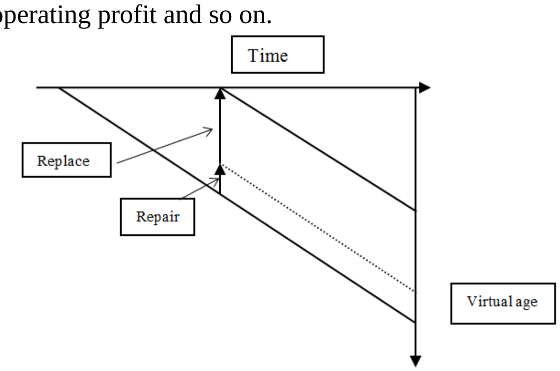

Fig.4: The Effect of Repair/Replace Decision on the Virtual Age [18].

Igbaet al.[19] have applied (RCM) in wind turbine power plant maintenance as a system thinking where the possible interaction between parts are identified. The study conducted on gearbox as it is considered the most critical part in the wind turbine since its failure is the main cause of wind turbine downtime[20]. The focus of this study was driven away from optimization functional failure analysis towards applying RCM in the early stages of product design so that it is not limited to the operational stage. The design engineers collect data from operational conditions and environment for design considerations and this require a close working relationship with suppliers. The output of this model will be by adjusting the product lifecycle management to cope with the field and operational conditions, a proper redesign of the product and service improvement.

V. CONCLUSION

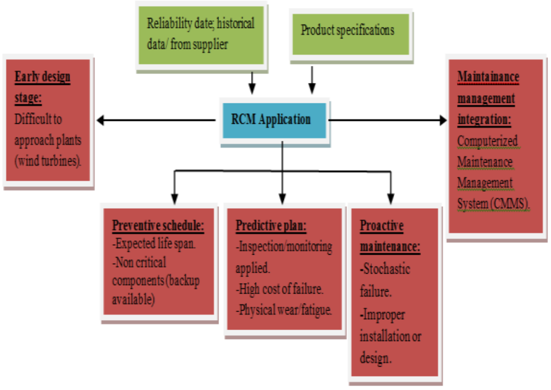

Fig.5: Summary of RCM application in Power Industry

This paper presents some of different approaches for RCM application in maintenance planning in power industries as shown in Fig.5. RCM is applied as maintenance planning tool for efficient maintenance planning in term of cost, reliability, safety and security. The reliability value of the system can be collected from the manufacturer [14] or by collecting historical data of the respective system [21]. In order to increase the reliability of a system higher frequency and quality of inspections can be implemented [17] but this implies financial losses. RCM therefore can be used to balance between maintenance cost minimizing and system value maximizing [18]. RCM can be time-based when the decision is based on planned time intervals or condition-based when the maintenance action is based on the results of inspections or monitoring [13]. Despite all the advantages of RCM, it is also time and effort consuming process especially with large complex plants (as studied by Perez-Canto and Rubio-Romero [7]), and it doesn't include management and human factors influence on the maintenance planning [4].

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