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A Condition-based Maintenance Strategy Considering Opportunistic Maintenance In Multiple Failure Modes

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Abstract. Multi-components electrical equipment has multiple failure modes. In the context of condition-based maintenance, it is inefficient if executing maintenance for a particular failure mode. Based on analysis of economic independence, opportunistic maintenance is a special preventive maintenance which can coordinate different maintenance for multiple failure mode. Furthermore, steady availability of equipment was quantified with inspection frequency and opportunistic maintenance strategy. Finally, maximizing steady availability of equipment with inspection frequency constraints to construct model. Feasibility and validity of the model are investigated through case study.

1. Introduction

Maintenance strategy has always been an important part of advanced asset management(AAM)[1]. In recent years, condition-based maintenance(CBM) has been proposed and applied in industry. In CBM, performance states of equipment can be obtained by diagnostic technology through inspection. Inspection frequency has been researched in many paper [2-4]. While there are many complicated equipment which is consists of multi-components, it is inefficient to maintenance only one particular failure mode [5-7].

In this paper, opportunistic maintenance is incorporated in multi-components equipment condition-based maintenance strategy. Opportunistic maintenance is a special preventive maintenance which is carried out to its failure mode when another failure is incurred. So it can reduce the whole down time and increase steady availability of equipment, coordinating different maintenance for multiple failure mode. Case is studied and analyzed to verify the performance of the proposed idea.

2. Equipment state transition process considering opportunistic maintenance strategy

Multi-states transition diagram is the basis of inspection and maintenance analyzing. as shown in Figure 1, two failure modes are considered in this diagram which are internal aging failure and external random failure. States 0,1,2,3 indicate a gradual aging failure in which state 0 indicates “normal”, state 1 indicates “needing minor overhaul”, state 2 indicates “needing major overhaul”, states 3 indicates “aging failure”. States 9,10,11 indicate a random failure in which state 9,10,11 indicate “random failure” from state 0,1,2 respectively. Other states such as state 5,6,9,10,11 indicate “inspection process”, state 7,8,12,13,14 indicate “maintenance process”. Square frames indicate strategies which can be chosen, they are not real states like other in circles. “NM” indicates non opportunistic maintenance, “M” indicates minor opportunistic maintenance and “MM” indicates major opportunistic maintenance.

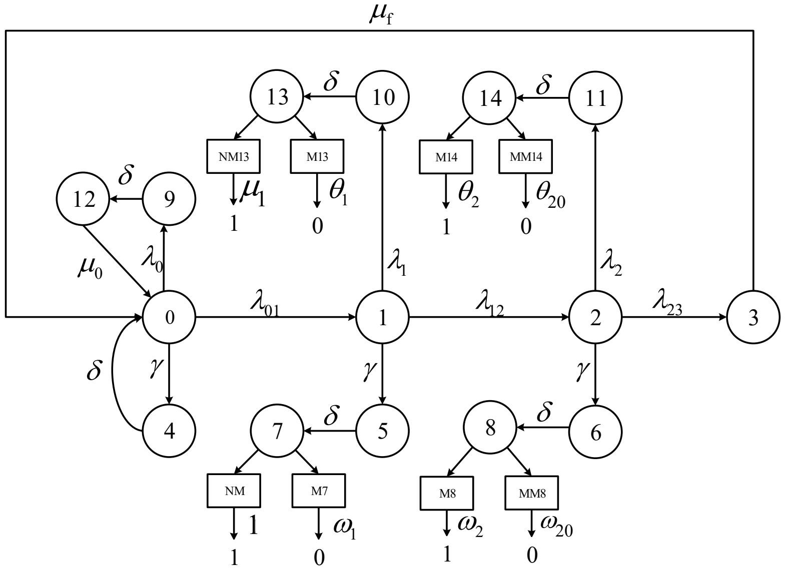

Figure 1. Integrated opportunistic maintenance and inspection model

All the transition rates in the diagram can be estimated from historical inspection records of the same type of equipment. Each transition rate is the number of the transition occurrences in the records divided by the corresponding recorded time length. Transition rates γ indicates inspection frequency which is not predefined. In this paper, opportunistic maintenance strategy are "M7", "MM8", "M13" and "MM14".

3. Optimization model of inspection frequency and opportunistic maintenance strategy

3.1. Objective function

The objective function aiming at maximizing the steady availability of equipment as follows:

$$Max \quad A = p_0 + p_1 + p_2 \tag{1}$$

where *A* is the steady availability of equipment, it indicates the probability of equipment operating in a such long time. *A* can be calculated by summing p_0, p_1, p_2 up, which indicate the probability of state 0, 1, 2.

3.2. Constraints

3.2.1. Inspection budget constraint.

Inspection frequency γ has its limit γ_{max} since operators of the equipment has a budget constraint, as follows:

$$0 < \gamma \le \gamma_{max} \tag{2}$$

3.2.2. States transition frequency balance constraint.

Assuming all the transition process between states are Markov process, states transition frequency must balance using Markov equations as (3)-(18):

$$p_0\lambda_0 + p_0\lambda_{01} + p_0\gamma = p_3\mu_f + p_4\delta + p_{12}\mu_0 \tag{3}$$

$$p_1\lambda_{12} + p_1\lambda_1 + p_1\gamma = p_0\lambda_{01} \tag{4}$$

$$p_2\lambda_2 + p_2\lambda_{23} + p_2\gamma = p_1\lambda_{12} \tag{5}$$

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$$p_3\mu_f = p_2\lambda_{23} \tag{6}$$

$$p_4\delta = p_0\gamma \tag{7}$$

$$p_5\delta = p_1\gamma \tag{8}$$

$$p_6\delta = p_2\gamma \tag{9}$$

$$p_7\omega_1 = p_5\delta \tag{10}$$

$$p_8\omega_{20} = p_6\delta \tag{11}$$

$$p_9\delta = p_0\lambda_0 \tag{12}$$

$$p_{10}\delta = p_1\lambda_1 \tag{13}$$

$$p_{11}\delta = p_2\lambda_2 \tag{14}$$

$$p_{12}\mu_0 = p_9\delta \tag{15}$$

$$p_{13}\theta_1 = p_{10}\delta \tag{16}$$

$$p_{14}\theta_{20} = p_{11}\delta \tag{17}$$

$$\sum_{i=0}^{14} p_i = 1 \tag{18}$$

where (18) is added to ensure that the sum of the probabilities of all the states in the diagram is 1.

4. Case Study

In order to verify the performance of the proposed idea, a case study is provided in this section. Table 1 lists out the parameters which were used in the model.

Table 1. Values of the Parameters.

Parameters	Value	Parameters	Value	Parameters	Value
λ_{01}	0.432	λ_2	0.5	δ	1460
λ_{12}	0.442	μ_0	873.6	ω_1	120
λ_{23}	1.004	μ_1	873.6	ω_2	120
λ_0	0.5	μ_2	873.6	ω_{20}	80
λ_1	0.5	μ_f	26	$\gamma_{\max}$	5

Two maintenance strategy has been established in this case study. Strategy I is traditional maintenance strategy which do not consider opportunistic maintenance, while strategy II considers opportunistic maintenance. The steady availability curve varying with inspection frequency and optimal results are shown as Figure (2) and Table 2.

As is shown in Figure (2), when inspection frequency increasing, availability of equipment increases first, and then decreases. This means inspection has its positive effect, but it will has negative effect when the frequency is too high. As is shown in Table 2, Contrasting two maintenance strategies, strategy II has higher optimal availability and lower optimal inspection frequency. It is clear that strategy II has its advantage comparing with Strategy I. Considering opportunistic maintenance is suitable for multi-components equipment.

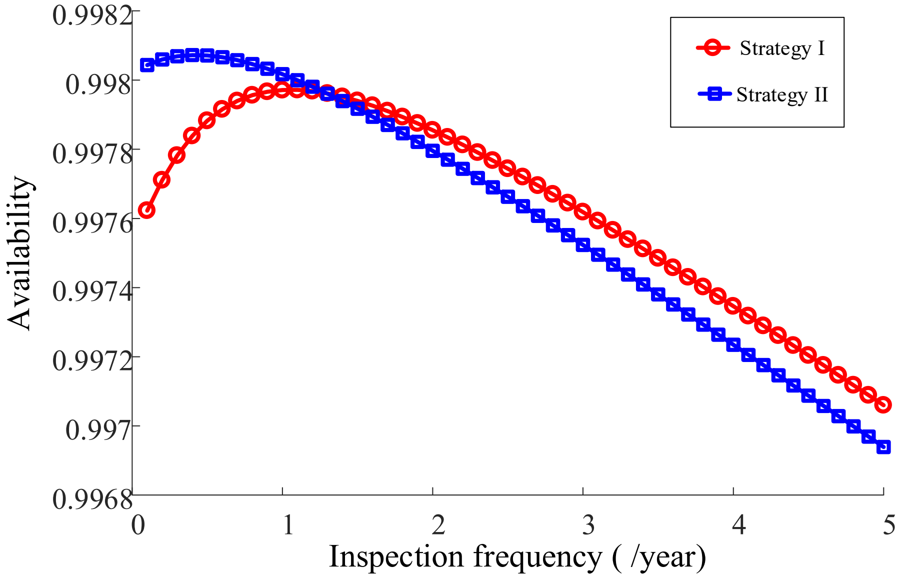

Figure 2. Availability of two maintenance strategy

Table 2. Results of Optimization.

	Strategy I	Strategy II
Optimal availability	0.9979	0.9981
Inspection frequency	1.4	0.4

5. Conclusion

A condition-based maintenance strategy is presented in this paper, in which opportunistic maintenance in multiple failure mode is considered. Using opportunistic maintenance to coordinate different failure mode is the feature of this paper. Based on multi-states diagram, an optimization model of inspection frequency is established. The case study indicates that incorporating opportunistic maintenance in condition-based maintenance strategy has its advantage in improving availability of equipment.

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