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To cite this article: Bo Xu *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **486** 012092

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Maintenance Scheduling of Power Equipment Considering Opportunistic Maintenance Strategy

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Abstract. This paper investigates the impact of opportunistic maintenance strategy on power equipment maintenance scheduling under economic dependence. The model focuses on power equipment with two types of failures: random failure and deterioration failure. Unlike previous research which didn't consider opportunistic maintenance between different failures modes, opportunistic maintenance strategy is proposed in this paper. In the opportunistic maintenance strategy, whenever random failure occurs, decision has to be made on whether deterioration failure is preventively maintained based on the degree of equipment deterioration and economic dependence. Firstly, Markov process is used to describe equipment state-space diagram. And then, in order to determine the optimal inspection rate, preventive maintenance threshold and opportunistic maintenance threshold of power equipment, the analytical expressions of inspection cost, maintenance cost, repair cost and outage cost are quantified. Finally, the total cost is minimized to get the optimal maintenance strategy. Case studies demonstrate the feasibility of the proposed model.

1. Introduction

Condition-based maintenance acquires the condition of power equipment by condition inspection. If the inspection interval is too large, it will be difficult to find the potential failures, resulting in large failure loss. If the inspection interval is too small, it will increase unnecessary inspection cost and maintenance cost. Therefore, appropriate inspection interval of power equipment can improve the reliability and economy of power system [1], [2], [3], [4].

Equipment inspection model is first proposed by Barlow in 1963 [5]. Since then, power equipment inspection strategy has been researched a lot. In [6] a cost-effective maintenance process is established and the effect of varying inspection rates on equipment reliability and maintenance cost is investigated. The use of state diagrams in modelling non-periodic inspections is discussed in [7], which makes it clear that using Markov processes must be judged critically when they are used for non-periodic inspections. The idea of using sub-states in modelling non-periodic inspections is originally proposed in [8], analytical method to compute equipment reliability indices is discussed. In [9], both repairable and aging failure modes are considered. An optimization model to determine equipment inspection interval is proposed by minimizing the total cost. In [10], hard failure model and soft failure model are used to model the failure process of GIS equipment. Equipment availability is derived taking



incomplete maintenance into consideration. In [11], substation level reliability and economic cost models are established. Optimal equipment maintenance rates that maximize substation reliability or minimize overall cost are determined. In [12], fuzzy Markov and Markov decision processes are proposed to deal with the uncertainty of equipment parameters. Optimal equipment maintenance rates can be got under fuzzy reliability indices and economic cost.

However, most, if not all, of the existing research on equipment maintenance strategies does not consider the economic dependence between different failure modes. In practice, combining maintenance activities of dependent failure modes can save maintenance cost and downtime than performing maintenance on each failure mode separately. To take this factor into account, opportunistic maintenance strategy is commonly used. In the opportunistic maintenance strategy, when a failure occurs, the opportunity to perform preventive maintenance on other failure modes is considered. Opportunistic maintenance strategy has been extensively studied in the past decades [13], [14]. Nevertheless, little research has explored the effects of opportunistic maintenance on power equipment maintenance scheduling. As opportunistic maintenance can reduce maintenance cost and system outage cost, this paper will optimize equipment maintenance strategies considering opportunistic maintenance strategy. The remainder of this paper is organized as follows. In Section 2, equipment state-space diagram considering opportunistic maintenance is proposed. In Section 3, equipment steady-state availability is mathematically quantified. The formulation of the maintenance optimization model is presented in Section 4. In Section 5, numerical studies and discussions are given to demonstrate the feasibility of the proposed model. Finally, conclusions are presented in Section 6.

2. Equipment state-space diagram considering opportunistic maintenance strategy

Figure 1 gives the state-space diagram of equipment k , which is represented by a sequence of wearing states. As is shown in Figure 1, the deterioration process of equipment k is modelled by three deterioration states: D_0 , D_1 and D_2 . F is the deterioration failure state and $\mu_{k,f}$ is the repair rate. Model parameters $\lambda_{k,01}$ and $\lambda_{k,12}$ are deterioration rates. $\lambda_{k,2F}$ is the transition rate from D_2 to F . Besides deterioration failure, equipment also suffers random failure. m_0 , m_1 and m_2 are random failure states. $\lambda_{k,0}$, $\lambda_{k,1}$ and $\lambda_{k,2}$ are the failure rates of random failure.

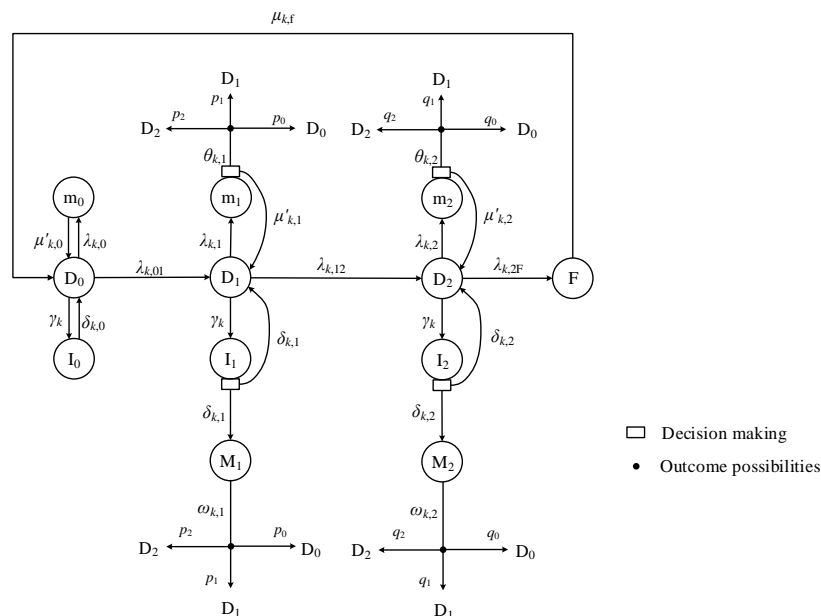


Figure 1. Equipment state-space diagram considering opportunistic maintenance strategy

In order to improve the condition of equipment, periodic inspection is carried out. I_0 , I_1 and I_2 are inspection states. γ_k is inspection rate. Inspections at I_0 reveal that equipment is in good condition and no preventive maintenance is required. Inspections at I_1 and I_2 reveal that equipment is deteriorated.

Let $D_{b(k)}$ be the preventive maintenance threshold of equipment k . If the condition of equipment k is found worse than $D_{b(k)}$, then preventive maintenance will be performed at state $D_{b(k)}$. As can be seen in this state diagram, inspections at I_1 and I_2 are followed by a decision making option (represented as rectangle) to determine preventive maintenance to be performed or not. M_1 and M_2 represent maintenance states. Different from previous research, to consider the effect of imperfect maintenance on equipment reliability, different outcome possibilities ($p_0, p_1, p_2, q_0, q_1, q_2$) of preventive maintenance are considered. After performing preventive maintenance, equipment may return either to the current state, or to better/worse state. $\omega_{k,i}$ is the transition rate from M_i to other deterioration states.

To take the advantage of economic dependence between different failure modes, opportunistic maintenance strategy is proposed. Opportunistic maintenance implies that the occurrence of random failure can provide an opportunity to perform preventive maintenance on deterioration failure; i.e., whether to perform opportunistic maintenance needs to be decided at the moment of random failure. In Figure 1, if random failure occurs, the equipment will be out of service. That's, the outage of any type of failure would result in the outage of the equipment. If we take this opportunity to perform preventive maintenance on the deterioration failure along with the repair of random failure, system outage cost and maintenance cost can be reduced. Assume that the impact of opportunistic maintenance on equipment reliability is the same with preventive maintenance. $D_{l(k)}$ is the opportunistic maintenance threshold of equipment k . At the moment of random failure, if the condition of equipment k is found worse than $D_{l(k)}$, then opportunistic maintenance will be performed. Let θ_i be the transition rate from m_i to other deterioration states.

As the actual deterioration of equipment can only be determined by inspection, it is necessary to increase opportunistic inspection at the moment of random failure. Taking economic dependence into account, the parameters associated with opportunistic maintenance strategy can be calculated as follows

$$u'_{k,i} = \frac{1}{\frac{1}{u_{k,i}} + \frac{1}{\delta_{k,i}}} = \frac{u_{k,i}\delta_{k,i}}{u_{k,i} + \delta_{k,i}}, i = 0, \dots, l(k) - 1 \quad (1)$$

$$\theta_{k,i} = \frac{1}{\frac{1}{u_{k,i}} + \frac{1}{\delta_{k,i}} + \frac{1}{\omega_{k,i}} - d_{k,s}} = \frac{u_{k,i}\delta_{k,i}\omega_{k,i}}{u_{k,i}\delta_{k,i} + u_{k,i}\omega_{k,i} + \delta_{k,i}\omega_{k,i} - u_{k,i}\delta_{k,i}\omega_{k,i}d_{k,s}}, i = l(k), \dots, 2 \quad (2)$$

Where $\mu_{k,i}$ is the repair rate of random failure, $d_{k,s}$ is the downtime saved when performing opportunistic maintenance which reflects the economic dependence between different failure modes.

3. Mathematical expression of equipment steady-state availability considering opportunistic maintenance

In this paper, the inspection rate, preventive maintenance threshold and opportunistic maintenance threshold of power equipment are our decision variables. Equipment steady-state availability is determined by these variables and is related to equipment steady-state probabilities. As the process in Figure 1 is homogeneous Markov process, the steady-state probabilities can be computed using equation (3) and (4).

$$\pi_k \Gamma_k = \pi_k \quad (3)$$

$$\pi_{k,D_0} + \pi_{k,D_1} + \dots + \pi_{k,F} = 1 \quad (4)$$

Where $\pi_k = (\pi_{k,D_0}, \pi_{k,D_1}, \dots, \pi_{k,F})$ is the steady-state probability vector of equipment k ; Γ_k is the transition rates matrix and can be computed using the state-space diagrams shown in Figure 1.

The steady-state availability of equipment k can be expressed as

$$A_k = \pi_{k,D_0} + \pi_{k,D_1} + \pi_{k,D_2} \quad (5)$$

4. Formulation of maintenance optimization model

4.1. Expected equipment cost

The expected equipment cost contains three parts: maintenance cost, repair cost and inspection cost.

(1) Expected maintenance cost

Maintenance cost is incurred from preventive maintenance and opportunistic maintenance. Expected maintenance cost is expressed as

$$CR_{k,P} = \sum_{i=b(k)}^2 \pi_{k,M_i} \omega_{k,i} C_{P,i}^k + \sum_{i=l(k)}^2 \pi_{k,m_i} \theta_{k,i} C_{P,i}^k \quad (6)$$

Where $C_{P,i}^k$ is the maintenance cost of equipment k in D_i .

(2) Expected repair cost

Repair cost is incurred from deterioration failure and random failure. Expected repair cost can be computed as

$$CR_{k,F} = \pi_{k,D_0} \lambda_{k,0} C_{F,m}^k + \pi_{k,D_1} \lambda_{k,1} C_{F,m}^k + \pi_{k,D_2} \lambda_{k,2} C_{F,m}^k + \pi_{k,D_2} \lambda_{k,2F} C_{F,M}^k \quad (7)$$

Where $C_{F,M}^k$ is the repair cost of deterioration failure of equipment k ; $C_{F,m}^k$ is the repair cost of random failure of equipment k .

(3) Expected inspection cost

If opportunistic maintenance is performed, then the inspection cost is incurred from periodic inspection and opportunistic inspection. The expected inspection cost is

$$CR_{k,I} = (\pi_{k,D_0} + \pi_{k,D_1} + \pi_{k,D_2}) \gamma_k C_I^k + \pi_{k,D_0} \lambda_{k,0} C_I^k + \pi_{k,D_1} \lambda_{k,1} C_I^k + \pi_{k,D_2} \lambda_{k,2} C_I^k \quad (8)$$

Expected maintenance cost, repair cost and inspection cost of equipment k can be formulated as

$$R_{k,eq} = CR_{k,P} + CR_{k,F} + CR_{k,I} \quad (9)$$

4.2. Expected system outage cost

The expected system outage cost due to equipment maintenance or failure can be mathematically formulated as

$$R_{sys} = \sum_{s \in S} \prod_{i=1}^{N-N_s} A_i \times \prod_{j=1}^{N_s} (1-A_j) \times L_s \times c_f \times 8760 \quad (10)$$

Where S is the set of scenarios that include equipment outage; L_s is the load curtailment in scenario s ; N is the number of equipment in the system; N_s is the number of equipment unavailable in scenario s ; c_f is penalty factor of load curtailment.

4.3. Objective function and constraint

The proposed maintenance optimization model is formulated in (11)-(13). Constraint (12) limits the maximum and minimum inspection rate. Constraint (13) gives the budget limit.

$$\min \sum_{k=1}^N R_{k,eq} + R_{sys} \quad (11)$$

subject to

$$\gamma_{k,min} \leq \gamma_k \leq \gamma_{k,max} \quad (12)$$

$$\sum_{k=1}^N CR_{k,P} \leq \text{Buget} \quad (13)$$

Genetic Algorithm is used to optimize the inspection rate, preventive maintenance threshold and opportunistic maintenance threshold of power equipment. More details about Genetic Algorithm can be seen from reference [15].

5. Case Studies

The proposed model is applied to typical substation configurations, which are depicted in Figure 2. For the sake of exposition, only transformer T1 are modeled with the proposed model. However, the model can also be extended to include other equipment as well. In addition, the availability of other

equipment is assumed to be 99.9%. The parameters setting for the transformer are given in Table 1. Each load point has constant average load demand 10MW. c_f is set to 1,053 yuan/MWh.

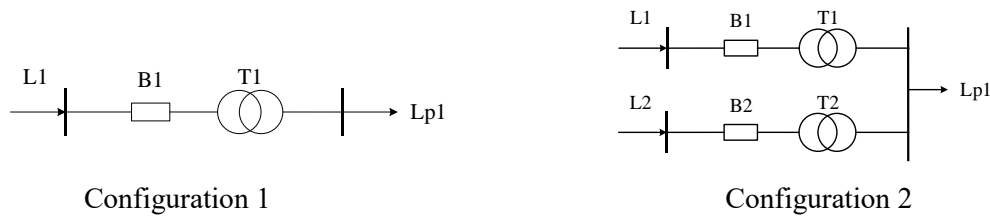


Figure 2. Substation configurations

Table 1. Parameters setting for the transformer

Parameter	Value	Parameter	Value
λ_{01}	0.105/year	ω_1	18/year
λ_{12}	0.105/year	ω_2	18/year
λ_{2F}	0.105/year	$C_{P,1}$	600,000 yuan
λ_0	0.008/year	$C_{P,2}$	600,000 yuan
λ_1	0.008/year	C_I	20,000 yuan
λ_2	0.008/year	$C_{F,m}$	100,000 yuan
μ_0	12.05/year	$C_{F,M}$	1,800,000 yuan
μ_1	12.05/year	p_0	0.8
μ_2	12.05/year	p_1	0.1
μ_f	3.04/year	p_2	0.1
δ_0	1095/year	q_0	0.6
δ_1	1095/year	q_1	0.3
δ_2	1095/year	q_2	0.1

5.1. Impact of opportunistic maintenance

To illustrate the impact of opportunistic maintenance, let $d_{T1,s}=15$ days. The following 6 maintenance strategies are analyzed. (1) Strategy 1, $D_b=D_1$, $D_f=D_1$. (2) Strategy 2, $D_b=D_1$, $D_f=D_2$. (3) Strategy 3, $D_b=D_1$, $D_f=F$. (4) Strategy 4, $D_b=D_2$, $D_f=D_1$. (5) Strategy 5, $D_b=D_2$, $D_f=D_2$. (6) Strategy 6, $D_b=D_2$, $D_f=F$.

Figure 3 compares transformer availability of the above 6 maintenance strategies. As shown in Figure 3, optimal maintenance strategy that maximizes transformer availability is Strategy 4 with inspection rate 1.1 times per year. When the inspection rate is low, potential failures may not be discovered, resulting in lower availability. On the other hand, when the inspection rate is high, unnecessary inspections and maintenance will decrease transformer availability.

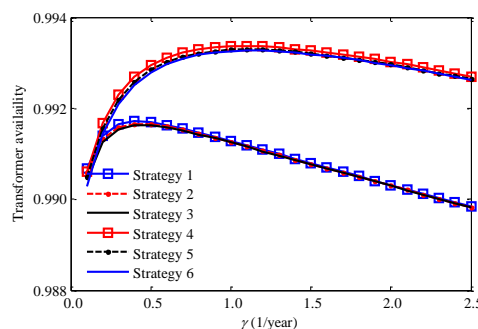


Figure 3. The variation of transformer availability with γ

5.2. The impact of economic dependence

In order to show the impact of the variation of economic dependence, let $d_{T1,s}=0$ day. Figure 4 compares transformer availability of the above 6 maintenance strategies. The optimal maintenance strategy is Strategy 5 with inspection rate 1.1 times per year, which is different from Figure 3.

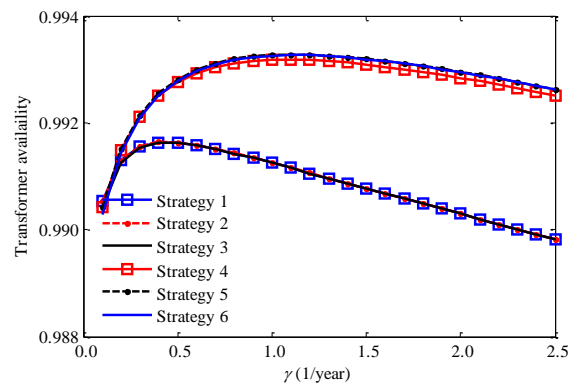


Figure 4. The variation of transformer availability with γ

5.3. Substation maintenance scheduling

Let $d_{T1,s}=15$ days. The total cost is minimized to optimize transformer maintenance strategies. Table 2 gives the corresponding results.

Table 2. Comparison of different maintenance strategies

Substation	Maintenance strategies	Optimal inspection rate (1/year)	Transformer cost (yuan)	System outage cost (yuan)	Total cost (yuan)
Configuration 1	Strategy 1	0.36	76,300	857,295	933,595
	Strategy 2	0.38	77,000	861,247	938,247
	Strategy 3	0.40	76,900	864,520	941,420
	Strategy 4	0.96	66,400	705,053	771,453
	Strategy 5	0.98	65,800	711,531	777,331
	Strategy 6	1.00	66,000	713,653	779,653
Configuration 2	Strategy 1	0.10	62,600	2,280	64,880
	Strategy 2	0.12	62,300	2,260	64,560
	Strategy 3	0.16	62,900	2,300	65,200
	Strategy 4	0.24	57,600	1,640	59,240
	Strategy 5	0.28	56,900	1,618	58,518
	Strategy 6	0.32	56,900	1,700	58,600

It can be seen from Table 2, the optimal maintenance strategy for Configuration 1 is strategy 4 with inspection rate 0.96 times per year. However, the optimal maintenance strategy for Configuration 2 is strategy 5 with inspection rate 0.28 times per year. The reason of the difference is that Configuration 2 can provide higher reliability than Configuration 1. In Configuration 1, system outage cost accounts for main sector of the total cost, whereas, transformer cost accounts for main sector of the total cost in Configuration 2.

6. Conclusions

This paper proposes a maintenance scheduling model for power equipment based on opportunistic maintenance strategy. The inspection rate, preventive maintenance threshold and opportunistic maintenance threshold of power equipment are optimized by minimizing the sum of maintenance cost, repair cost, inspection cost, and system outage cost. Case studies demonstrate that opportunistic maintenance can improve equipment availability and reduce the total cost. However, as opportunistic maintenance strategy depends on the economic dependence between different failure modes, it must be judged critically when it is used for other situations.

Acknowledgement

This paper is supported by the National Key Research and Development Program of China (2016YFB0900100), the Science and Technology Project of State Grid Corporation of China “Research on regional integrated energy supply systems modelling and planning techniques”.

References

- [1] Abeygunawardane S K, Jirutitijaroen P. Application of Probabilistic Maintenance Models for Selecting Optimal Inspection Rates Considering Reliability and Cost Tradeoff. *IEEE Trans. Power Deliv.*, 2014, 29, 1, pp. 178-186.
- [2] Chan G K, Asgarpour S. Optimum Maintenance Policy with Markov Processes. *Elect. Power Syst. Res.*, 2006, 76, 6, pp. 452-456.
- [3] Tomasevicz C L, Asgarpour S. Optimum Maintenance Policy Using Semi-Markov Decision Processes. *Elect. Power Syst. Res.*, 2009, 79, 9, pp. 1286-1291.
- [4] Moslemi N, Kazemi M, Abedi S M, et al. Maintenance Scheduling of Transmission Systems Considering Coordinated Outages. *IEEE Syst. J.*, in press.
- [5] Barlow R E, Hunter L C, Proschan F. Optimum Checking Procedures. *SIAM J.*, 1963, 11, 4, pp. 1078-1095.
- [6] Jirutitijaroen P, Singh C. The Effect of Transformer Maintenance Parameters on Reliability and Cost: A Probabilistic Model. *Elect. Power Syst. Res.*, 2004, 72, 3, pp. 213-224.
- [7] Welte T M. Using State Diagrams for Modeling Maintenance of Deteriorating Systems. *IEEE Trans. Power Syst.*, 2009, 24, 1, pp. 58-66.
- [8] Abeygunawardane S K, Jirutitijaroen P. New State Diagrams for Probabilistic Maintenance Models. *IEEE Trans. Power Syst.*, 2011, 26, 4, pp. 2207-2213.
- [9] Zhong J, Li W, Wang C, et al. Determining Optimal Inspection Intervals in Maintenance Considering Equipment Aging Failures. *IEEE Trans. on Power Syst.*, 2017, 32, 2, pp. 1474-1482.
- [10] Wang Q, He Z, Lin S, et al. Failure Modeling and Maintenance Decision for GIS Equipment Subject to Degradation and Shocks. *IEEE Trans. Power Deliv.*, 2017, 32, 2, pp. 1079-1088.
- [11] Ge H, Asgarpour S. Reliability and Maintainability Improvement of Substations With Aging Infrastructure. *IEEE Trans. Power Deliv.*, 2012, 27, 4, pp. 1868-1876.
- [12] Ge H, Asgarpour S. Reliability Evaluation of Equipment and Substations With Fuzzy Markov Processes. *IEEE Trans. on Power Syst.*, 2010, 25, 3, pp. 1319-1328.
- [13] Ding F, Tian Z. Opportunistic Maintenance for Wind Farms Considering Multi-level Imperfect Maintenance Thresholds. *Renewable Energy*, 2012, 45, 3, pp. 175-182.
- [14] Shafiee M, Finkelstein M, B érenguer C. An Opportunistic Condition-based Maintenance Policy for Offshore Wind Turbine Blades Subjected to Degradation and Environmental Shocks. *Reliability Engineering & System Safety*, 2015, 142, pp. 463-471.
- [15] Heo J H, Kim M K, Park G P, et al. A Reliability-Centered Approach to an Optimal Maintenance Strategy in Transmission Systems Using a Genetic Algorithm. *IEEE Trans. Power Deliv.*, 2011, 26, 4, pp. 2171-2179.