Short-term Power System Maintenance Scheduling with Imperfect Repair

Bo Xu¹, Shenzhi Xu¹ and Yumin Zhang²

1 State Grid Energy Research Institute Co., Ltd., Beijing, China
2 College of Electrical Engineering and Automation, Shandong University of Science and Technology, Qingdao, China

¹ Corresponding author: zymeth@126.com

Abstract. Most of the existing research in short-term power system maintenance scheduling assumes that repair is minimal when equipment fails. However, this may not always be the truth because sometimes repair after failure is imperfect. This paper investigates the impact of imperfect repair on power system maintenance scheduling. Unlike previous research which didn’t consider imperfect repair, a condition-based maintenance optimization model is proposed. The model focuses on equipment deterioration failure. Firstly, a new equipment state-space diagram under imperfect repair is given. And then, the availability of power equipment considering maintenance schedule and imperfect repair is derived using the Markov process theory. Based on that, in order to determine the optimal equipment maintenance schedules, the expression of system outage cost is given. Finally, system outage cost is minimized to optimize equipment maintenance schedules. A case study is used to illustrate the effectiveness and significance of the proposed model.

1. Introduction

With the expansion of power system, power equipment maintenance strategies has been paid more and more attention. Recently, the development of condition-based maintenance technology has made it possible to prolong power equipment service life and improve the reliability and economy of power system operation [1], [2], [3].

Traditional condition-based maintenance decisions are made according to the condition of individual power equipment [4], [5]. However, as power system is composed of multi-equipment, traditional research can’t take into account the impact of equipment maintenance on the system operation, thus resulting in high system operation risk. In recent years, equipment condition-based maintenance scheduling from systematic perspective has become a hot research topic. For example, reference [6] proposes a mixed-integer linear model for the mid-term maintenance scheduling of thermal units with decoupled failure rates. Case studies demonstrate the effectiveness and computational efficiency of the proposed model. References [7]-[8] present a two-stage maintenance scheduler to coordinate the mid-term and short-term maintenance scheduling of transformers considering actual transformer condition and N-1 security constraints. In another two part paper [9] and [10], a new generation maintenance framework is presented. In [9], a mixed-integer optimization model for generation maintenance scheduling is proposed considering the dynamic information of generators’ health and maintenance cost. In [10], the model proposed in [9] is extended to consider the effects of maintenance on network operation. An integrated framework based on covariates is
proposed in [11]. Short-term generation and transmission maintenance scheduling with midterm maintenance decisions are coordinated by considering short-term security-constrained unit commitment. [12] integrates condition-based maintenance and operations scheduling for generators considering unexpected failures. However, most of the existing research assumes that repair is minimal when power equipment fails. This may not always be the truth because sometimes repair after failure is imperfect in the reality. Nevertheless, little research has explored the effects of imperfect repair on short-term power system maintenance scheduling. This paper will fill this gap. In our proposed model, we model the imperfect repair of power equipment, and highlight the difference between imperfect repair, minimal repair and perfect repair. We demonstrate the equipment state-space diagram with imperfect repair in Section 2. In Section 3, we derive equipment availability which considers the equipment maintenance schedule and imperfect repair. Section 4 gives the maintenance optimization model which minimizes system outage cost. Section 5 uses a case study to bring the mathematical model to life. Section 6 summarizes and recommends the future work.

2. Equipment state-space diagram considering imperfect repair

Figure 1 gives a new equipment state-space diagram. As shown in Figure 1, a four-state Markov model is used to describe the outage process of equipment $k$. State 1 is the deteriorated state with high failure rate, while state 3 is the “as good as new” state and the corresponding failure rate is very low. State 2 and state 4 are the failure states. The repair in state 2 may return equipment either to state 1 (minimal repair) with probability $p$ or to state 3 (perfect repair) with probability $q$ where $p+q=1$. That is, the repair upon failure is imperfect and equipment condition may be improved or may not be affected after repair. Let $\lambda_{k,1}$ be the failure rate of equipment $k$ in state 1. $\mu_k$ is the repair rate. $\lambda_{k,0}$ is the failure rate of equipment $k$ in state 3.

![Figure 1. Equipment state-space diagram with imperfect repair](image)

In (1), $P_{k,j}^s(t)-P_{k,j}^s(t)$ represent the probability of state 1~4 for equipment $k$ given the initial state $s_k$. Taking the boundary condition, $P_{k,j}^s(t)+P_{k,j}^s(t)+P_{k,j}^s(t)+P_{k,j}^s(t)=1$, into account, then $P_{k,j}^s(t)$ ($j=1,2,3,4$) can be calculated using Equation (1).

The availability of equipment $k$ can be expressed as

$$A_k^s(t) = P_{k,1}^s(t) + P_{k,3}^s(t)$$

3. Derivation of power equipment availability considering maintenance schedule and imperfect repair

Figure 2 generally illustrates the proposed model. In Figure 2, $T$ is the maintenance planning horizon. $M_k$ is the starting time of the planned preventive maintenance (PM). $d_k$ is the duration of planned PM.
If deterioration failure occurs before the planned PM, the equipment will be out of service. If equipment \( k \) is repair to state 3 after deterioration failure, the planned PM will be cancelled. However, if equipment \( k \) is repair to state 1 after failure, the PM will be performed as planned.

\[
\text{Maintenance planning horizon } T
\]

![Figure 2. Illustration of the proposed model](image)

The following two cases are considered to compute equipment availability [13].

1) Case1: no failure occurs during the time interval \([0, M_k]\).

As no failure occurs during the time interval \([0, M_k]\), the planned PM will be carried out at time \( M_k \).

After the planned PM, the equipment is repaired to state 3. Hence, the equipment availability associated with this case can be written as

\[
A_{k,\text{case1}}(t) = \begin{cases} 
1 - F_k(t), & t < M_k \\
0, & M_k \leq t < M_k + d_k \\
\left[1 - F_k(M_k)\right] A_k^3(t - M_k - d_k), & M_k + d_k \leq t \leq T
\end{cases}
\]

(3)

Where \( F_k(t) \) is the failure distribution function of equipment \( k \) and it can be formulated as

\[
F_k(t) = 1 - e^{-\lambda_k t}
\]

(4)

2) Case2: deterioration failure occurs during the time interval \([0, M_k]\).

When deterioration failure occurs, the equipment may be repaired to state 3 with probability \( q \) or be repaired to state 1 with probability \( p \). In the former case, the planned PM in the time interval \([M_k, M_k + d_k]\) will be cancelled. However, in the latter case, the cancelation of the planned PM will not be incurred from this time of repair. Therefore, the equipment availability in this case can be formulated as

\[
A_{k,\text{case2}}(t) = \lambda_k \left[1 - F_k(M_k)\right] A_k^3(t - M_k - d_k) + \sum_{i=1}^{4} p_{ij}^3(M_k - u) A_k^i(t - M_k - d_k)
\]

(5)

Where \( \lambda_k(t - u) \) represents the availability of equipment \( k \) at time \( t \) \((M_k \leq t \leq T)\) given that it failed at time \( u \). \( \lambda_k(t - u) \) can be written as

\[
\lambda_k(t - u) = \begin{cases} 
\sum_{i=1}^{4} p_{ij}^3(M_k - u) A_k^i(t - M_k), & M_k \leq t < M_k + d_k \\
\sum_{i=1}^{4} p_{ij}^3(M_k - u) A_k^i(t - M_k) + \sum_{i=1}^{4} p_{ij}^3(M_k - u) A_k^i(t - M_k - d_k), & M_k \leq t \leq T
\end{cases}
\]

(6)

Combining the two cases mentioned above, equipment availability function considering the planned PM and imperfect repair can be computed as

\[
A_k(t) = A_{k,\text{case1}}(t) + A_{k,\text{case2}}(t)
\]

(7)

4. Formulation of system maintenance optimization model

The system expected outage cost due to equipment maintenance or failure over the given planning horizon \( T \) is mathematically formulated as

\[
E[R^T] = \sum_{t=1}^{T} \sum_{s=1}^{N_s} \pi_s(t) \text{sev}_s(t) H_s \text{e}_f
\]

(8)
\[
\pi_s(t) = \prod_{j=1}^{m} A_j(t) \prod_{l=1}^{n-m} [1 - A_l(t)]
\]  
(9)

Where \( s \) represents the system contingency; \( N_s \) is the number of contingencies in the system; \( \pi_s(t) \) is the probability of occurrence of contingency \( s \); \( \text{sev}_s(t) \) is the loss of load due to contingency \( s \) in period \( t \); \( H_w \) is the number of hours in each period; \( c_l \) is penalty factor of load curtailment; \( n \) is the number of equipment in the system; \( m_s \) is the number of equipment available in contingency \( s \).

The objective of the proposed model is to minimize the system outage cost

\[
\text{Minimize } E[R']
\]  
(10)

The associated constraints are formulated as follows.

\[
\begin{cases}
X_k(t) \in \{0,1\}, & \text{if } e_k \leq t \leq l_k + d_k \\
X_k(t) = 0, & \text{otherwise}
\end{cases}
\]  
(11)

\[
\sum_{t=1}^{T} X_k(t) = d_k, \quad \forall k
\]  
(12)

\[
\sum_{k=1}^{n} r_k X_k(t) \leq r_{\text{max}}(t), \quad \forall t
\]  
(13)

Where \( X_k(t) \) is equal to 1 if the planned PM is performed on equipment \( k \) in period \( t \) and 0 otherwise. \( e_k \) is the earliest time to perform PM on equipment \( k \). \( l_k \) is the latest time to perform PM on equipment \( k \). \( r_k \) represents the amount of resources necessary for performing PM on equipment \( k \). \( r_{\text{max}}(t) \) is the available resource in period \( t \).

Our objective is to optimize the maintenance schedule for power equipment. Thus, \( M_1, M_2, \ldots, M_n \) are decision variables. As the objective function of the proposed mode is non-linear, genetic algorithm (GA) is used to solve the optimization model. Although GA cannot always guarantee the global optimum solutions, it has become a fast and effective tool to find the near-optimal solutions. More details about GA can be seen from reference [14].

5. Case Study

In this section, we present a case study to investigate the effectiveness of the proposed model. The model is applied to a typical substation, which is depicted in Figure 3. We examine how imperfect repair affects equipment maintenance scheduling. The substation consists of 4 generating units, 4 transformers, 11 breakers and 2 load points. For simplicity, only transformers T1, T2, T3 and T4 are modelled with the proposed model. Other equipment are assumed to be reliable during the maintenance planning horizon. The parameters used are given in Table 1. The planning horizon is 52 weeks divided into 52 equal time intervals. The load curve of load point Lp1 and Lp2 over the planning horizon is shown in Figure 4.

![Figure 3. Substation configurations](image-url)
Figure 4. Weekly load curve of load point Lp1 and Lp2

Table 1. Parameters setting for transformers

| Transformers | \( \lambda_1 \) (1/week) | \( \lambda_0 \) (1/week) | \( \mu \) (1/week) | \( d \) (week) |
|--------------|--------------------------|--------------------------|-------------------|--------------|
| T1           | 0.015                    | 0.0083                   | 0.35              | 2            |
| T2           | 0.017                    | 0.008                    | 0.35              | 2            |
| T3           | 0.012                    | 0.0075                   | 0.35              | 2            |
| T4           | 0.02                     | 0.0077                   | 0.35              | 2            |

To show the impacts of imperfect repair on transformer maintenance scheduling, the following three scenarios are analysed.

1) Scenario 1: The planned PM of transformer T1 is scheduled in the 34th period (\( M = 34 \) week) and the parameter is set as 0.
2) Scenario 2: The same as Scenario 1 except \( p = 0.5 \).
3) Scenario 3: The same as Scenario 1 except \( p = 1 \).

Figure 5 and Figure 6 compare the transformer availability curves of the three scenarios mentioned above.

Figure 5. The variation of transformer availability
Figure 6. The variation of transformer availability within the interval [0.95, 1.0]

It can be seen from Figure 5 and Figure 6, during the time period [0, 34), as parameter is going to be closer to 0, transformer availability will be much higher which is quite reasonable because equipment is more likely to be restored to the state 3 with smaller . During the planning PM period [34, 36], transformer availability in scenario 1 is also much higher than the other scenarios. The reason is that the probability of cancellation of the planned PM is increased in scenario 1 which results in the reduced probability of planned outage. In addition, for the availability curve in scenario 3, the unavailability during the period [34, 36] is 1. That’s because equipment is minimally repaired during the time period [0, 34) and the planned PM is performed with probability 1.

Let $c_r$=1,053 $/MWh. Table 2 gives the substation outage cost corresponding to different scenarios.

| Scenarios | System outage cost ($) |
|-----------|------------------------|
| Scenario 1 | 3337.5                  |
| Scenario 2 | 3391.1                  |
| Scenario 3 | 3649.4                  |

It can be seen from Table 2, system outage cost in Scenario 1, Scenario 2 and Scenario 3 are 3337.5$, 3391.1$ and 3649.4$, respectively. In Scenario 3, the repair is minimal. In Scenario 1, the repair after failure is perfect. It is found to be the most cost-effective. A total cost of 8.5% will be reduced compared with Scenario 3. Thus, we can see that the impact of repair on system operation varies with different repair strategies.

Given $p$=0.5, the model proposed in section 4 is solved. Table 3 gives the maintenance decisions.

| Transformers | Maintenance schedule (week) |
|--------------|-----------------------------|
| $T_1$        | 35                          |
| $T_2$        | 13                          |
| $T_3$        | 38                          |
| $T_4$        | 11                          |

| System outage cost ($) | 3088.4                      |

It can be seen from Table 3, the initial failure rates of transformers $T_2$ and $T_4$ are higher than the other transformers, resulting in earlier maintenance schedule. However, the initial failure rates of transformers $T_1$ and $T_3$ are lower, resulting in later maintenance schedule. The total cost under imperfect repair is 3088.4 $. This study reflect the effectiveness of this paper in modelling imperfect repair.

6. Conclusions
In this paper, we presented a novel modelling method for system maintenance scheduling with imperfect repair. We showed that imperfect repair has non-negligible impact on equipment availability. A maintenance optimization model is proposed, which minimize system outage cost considering maintenance constraints. The validity and significance of the model are verified by a case study. We demonstrated that the impact of imperfect repair on system operation is between perfect repair and minimal repair. In further research, the model in this paper can be easily extended to incorporate economic dependence between different power equipment in the power system.

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