Condition-based Maintenance with Imperfect Inspections for the GIL Subject to Continuous Degradation and Random Shocks

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Abstract—**In recent decades, the gas insulated transmission line (GIL) has been developed as a reliable technology for electric power transmission. The GIL are subject to degradation-shock-based competing failure modes of SF6 gas leakage and partial discharge. To maintain the high reliability of the GIL in its long lifetime, condition-based maintenance (CBM) can be designed based on inspected degradation levels. However, due to the complex inner structures and limited inspection environment of the GIL, the SF6 leakage rate cannot always be perfectly inspected. Therefore, this paper proposes a new CBM strategy with imperfect inspections for the GIL. Based on the concepts of false positive (FP) and false negative (FN) incurred by imperfect inspections, long run cost rate is computed under three different scenarios of maintenance actions, i.e., ending up with corrective maintenance (CM) for soft failure, CM for hard failure, and preventive maintenance (PM). The optimal inspection interval and preventive maintenance threshold are obtained by minimizing the long run cost rate. A numerical example illustrates the effectiveness of the proposed strategy, and sensitivity analysis is conducted to study the effects of imperfect inspection cost and inspection error.**

Keywords- the GIL, condition-based maintenance, imperfect inspections, continuous degradation, random shocks

I. INTRODUCTION

Thanks to the excellent insulating property of SF6 in the tubular conductor, the gas insulated transmission line (GIL) has been developed as an alternative underground technology for electric power transmission [1]. And as a typical electromechanical system, the GIL has shown high efficiency and reliability concerning both mechanical failure and electrical endurance [2]. Considering that the GIL are usually operated with high load and in harsh environment, which may cause various failures, it is significant to design considerable maintenance strategies to avoid the occurrence of failures and save its lifetime cycle cost.

In fact, the GIL is subject to both continuous degradation and random shocks [3], which are respectively caused by SF6 leakage [4] and partial discharge [5], and this is similar to the competing failure process of the gas insulated switchgear (GIS) [6]. Therefore, many studies have been devoted to the reliability modelling and maintenance strategy optimization of the GIS or the GIL. Considering both dependent competing failure process and random degradation initiation time, Hao and Yang proposed a new reliability model for the GIL [7]. By maximizing the reliability and minimizing the long-run maintenance cost, Wang et.al investigated the maintenance strategy for the GIS, and obtained the optimal inspection interval and shock failure threshold [8]. This strategy is further extended in [9], by considering the dependence between degradation process and shocks, and also the balance of availability and economic efficiency.

However, one big problem for the mentioned maintenance strategies is that the inspections are all assumed to be perfect. In practice, degradation levels of an on-going system are usually monitored by embedded sensors, which may be contaminated by random inspection errors [10]. This is exactly the case of SF6 leakage rate inspection, which is due to the complex inner structures and limited inspection environment of the GIL. By comparing different gas pressure sensors in the GIS, Kamei and Takai studied the effect of condition information accuracy on CBM strategy [11]. More theoretical CBM models with imperfect inspections can be referred to [12-13], Berrade, Scarf, Cavalcante and Dwight proposed a new inspection and replacement policy for a three-state system, with the consideration of FPs and FNs [14]. Based on the continuous Gamma degradation process model, Huynh, Barros and Bérenguer developed a novel CBM decision framework with inspection errors [15].

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To the best of our knowledge, researches on CBM strategy optimization with imperfect inspections are still limited for systems subject to competing failure processes. This enables us to present cost analysis and optimization of the proposed inspection and maintenance policy. In order to obtain the optimal inspection interval and preventive maintenance threshold level, the remainder of this paper is organized in the following structure. In Section 2, some basic assumptions are listed for the competing failure processes and the CBM strategy of the GIL. Section 3 presents the CBM strategy optimization challenge introduced by imperfect inspections. Cost analysis of the strategy is conducted in Section 4, and some numerical examples are provided in Section 5. Section 6 concludes the paper with some insights and perspectives.

II. BASIC ASSUMPTIONS FOR THE MAINTENANCE STRATEGY

For the GIL subject to continuous degradation and random shocks, both preventive and corrective maintenance actions are conducted according to periodic inspections contaminated by random errors. To optimize such a CBM strategy, some basic assumptions are presented at first:

1) The actual degradation process of the GIL is modelled by a homogeneous Gamma process $X(t)$, i.e., $X(t)-X(0)\sim Ga(\alpha t,\beta)$, whose cumulative distribution function (CDF) is denoted by $F_X(x;t)$. Without loss of generality, $X(0)$ is assumed to be 0 for illustration;

2) The arrival of random shocks obeys a homogenous Poisson process with rate λ_0, and $N(t)$ denotes the total number of shocks arrived before t. In addition, the level of each shock is a normal variable $W\sim N\left(\mu_W,\sigma_W^2\right)$, whose CDF is denoted by $F_W(x)$;

3) Inspections of the degradation levels can be either perfect or imperfect, but all with constant inspection interval τ. Perfect inspections can reveal the actual degradation levels, while the imperfect inspections are contaminated by random errors:

$$Z_m = X_m + \varepsilon_m \tag{1}$$

where $X_m = X(t_m)$, $Z_m = Z(t_m)$ and $\varepsilon_m = \varepsilon(t_m)\sim N\left(0,\sigma_\varepsilon^2\right)$ are respectively the imperfectly inspected degradation level, the actual degradation level and the inspection error at the mth inspection time $t_m = m\tau$;

4) A soft failure happens once the actual degradation level is greater than the threshold level d_{CM}, and a hard failure is caused by an arriving shock with magnitude exceeding d_{HF}. These two failure modes are competing and also independent, and their occurrence are assumed to be self-announcing;

5) Confronted with either soft or hard failure, a corrective maintenance will be carried out. Besides, a preventive maintenance action is designed when the inspected degradation level exceeds d_{PM}, which is a decision variable to be optimized. Both maintenance actions will make the GIL back to as-good-as-new condition;

6) Cost for each imperfect inspection, perfect inspection, preventive maintenance and corrective maintenance is respectively C_{II}, C_{PI}, C_{PM} and C_{CM}. And durations for both inspections and maintenance actions are negligible.

III. PERFORMANCE OF A MAINTENANCE STRATEGY WITH IMPERFECT INSPECTIONS

To design an optimal inspection interval τ and preventive maintenance threshold level d_{PM}, we use the long run cost rate to evaluate the performance of a CBM strategy, which is defined based on the theory of renewal process [31]:

$$C_\infty = \lim_{t\to\infty}\frac{C(t)}{t} = \frac{E\left[C(L)\right]}{E(L)} \tag{2}$$

where $E\left[C(L)\right]$ and $E(L)$ are respectively the expected cost and length of a renewal cycle.

Note that the decision of conducting preventive maintenance or doing nothing is made according to the imperfect inspection results. However, as can be seen in Table I, a total of four cases are possible for each inspection: true positive (**TP**), false positive (**FP**), true negative (**TN**) and false negative (**FN**), where "negative" means the degradation level does not exceed d_{PM}, and "positive" means the opposite.

TABLE I. FOUR POSSIBLE CASES FOR EACH IMPERFECT INSPECTION

Inspection result		**Actual degradation level**	
		Positive	***Negative***
Inspected degradation level	***Positive***	TP	FP
	Negative	FN	TN

Therefore, for the mth inspection, the occurrence probabilities for different cases are calculated as:

$$P(TP_m) = P\left\{d_{PM} < X_m \le d_{CM}, d_{PM} < Z_m \le d_{CM}\right\} \tag{3}$$

$$P(FP_m) = P\left\{X_m \le d_{PM}, d_{PM} < Z_m \le d_{CM}\right\} \tag{4}$$

$$P(TN_m) = P\left\{X_m \le d_{PM}, Z_m \le d_{PM}\right\} \tag{5}$$

$$P(FN_m) = P\left\{d_{PM} < X_m \le d_{PM}, Z_m \le d_{PM}\right\} \tag{6}$$

Due to the property of the Gamma process, degradation levels of the GIL at two inspection times are not independent. Therefore, in order to derive the expected cost and length of a renewal cycle, first we have to compute the conditional occurrence probability for possible results of two successive inspections. Taking the conditional event $TN_n \mid TN_{n-1}, n\ge 2$ as an example, its schematic diagram is shown in Fig. 1 and its probability is derived in Eq. (7). And for other possible conditional events, similar results can be obtained by changing the limits of integration or the integral functions.

$$
\begin{aligned}
&P\left(TN_n \mid TN_{n-1}\right)=P\left\{X_n \le d_{PM}, Z_n \le d_{PM} \mid X_{n-1} \le d_{PM}, Z_{n-1} \le d_{PM}\right\} \\
&=\frac{P\left\{X_n \le d_{PM}, Z_n \le d_{PM}, X_{n-1} \le d_{PM}, Z_{n-1} \le d_{PM}\right\}}{P\left\{X_{n-1} \le d_{PM}, Z_{n-1} \le d_{PM}\right\}} \\
&=\frac{\int_0^{d_{PM}} \int_0^{d_{PM}-x} \Phi\left(\dfrac{d_{PM}-x-y}{\sigma_\varepsilon}\right) f_{\Delta X_{n-1,n}}(y) dy \cdot \Phi\left(\dfrac{d_{PM}-x}{\sigma_\varepsilon}\right) f_{X_{n-1}}(x) dx}{\int_0^{d_{PM}} \Phi\left(\dfrac{d_{PM}-x}{\sigma_\varepsilon}\right) f_{X_{n-1}}(x) dx}
\end{aligned} \tag{7}
$$

where the PDFs of $\Delta X_{n-1,n}=X_n-X_{n-1}$ and X_{n-1} can both be referred to (1).

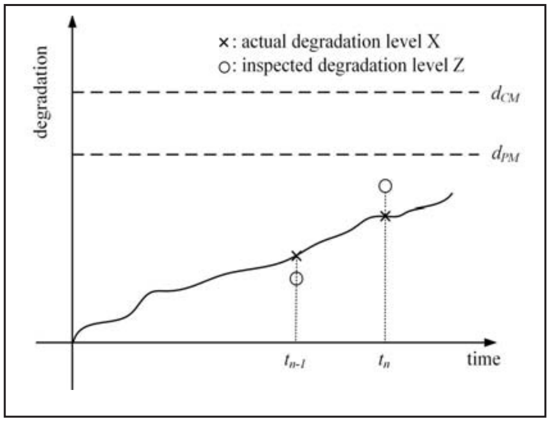

Figure 1. Schematic diagram for the conditional event $TN_n \mid TN_{n-1}$

IV. COST ANALYSIS FOR THE MAINTENANCE STRATEGY

Assume that the actual and inspected degradation levels exceed d_{PM} at time intervals $\left[(i-1)\tau, i\tau\right]$ and $\left[(j-1)\tau, j\tau\right]$, respectively. Besides, without the consideration of maintenance, soft failure and hard failure respectively occur at T_{SF} and T_{HF}. Then based on the occurrence probabilities for conditional events, we can derive the probabilities for the renewal cycle in the following three cases, i.e., ending up with CM for soft failure, CM for hard failure, and PM.

Case 1: The renewal cycle ends up with CM for soft failure.

In this case, soft failure occurs before hard failure. Therefore, the magnitude of arrived shocks before T_{SF} are no larger than d_{HF}. And according to whether there is FP, the degradation path of this case can be divided into two subcases:

(1) The actual degradation path first exceeds d_{CM} at time interval $\left[(k-1)\tau, k\tau\right]$, and the first $(k-1)$ inspected degradation levels are smaller than d_{PM}, where $k=\lfloor T_{SF}/\tau \rfloor$ is the number of inspections before the soft failure time T_{SF};

(2) The actual degradation path first exceeds d_{PM} at time interval $\left[(i-1)\tau, i\tau\right], i<k$, but FPs occur for the i^{th} to the $(k-1)^{th}$ inspections, and the actual degradation level first exceeds d_{CM} at time interval $\left[(k-1)\tau, k\tau\right]$.

Therefore, on condition of given $T_{SF} \in (0,+\infty)$, the probability of case 1 is:

$$
P_1\left(T_{SF}\right)=P_1^H\left(T_{SF}\right) \cdot P_1^D\left(T_{SF}\right) \tag{8}
$$

where $P_1^H\left(T_{SF}\right)$ is the probability of no hard failure by T_{SF}, and $P_1^D\left(T_{SF}\right)$ is the probability for the degradation path before soft failure at T_{SF}.

$$
\begin{aligned}
P_1^H\left(T_{SF}\right) &=\sum_{r=0}^{+\infty}\left\{\left[F_W\left(d_{HF}\right)\right]^r P\left[N\left(T_{SF}\right)=r\right]\right\} \\
&=\sum_{r=0}^{+\infty}\left\{\left[F_W\left(d_{HF}\right)\right]^r \left(\lambda_0 T_{SF}\right)^r e^{-\lambda_0 T_{SF}} / r!\right\}
\end{aligned} \tag{9}
$$

$$
\begin{aligned}
P_1^D\left(T_{SF}\right)=&P\left(TN_1, TN_2, \cdots, TN_{k-1}, X_k \ge d_{CM}\right) \\
&+\sum_{i=1}^{k-1} P\left(TN_1, \cdots, TN_{i-1}, FN_i, \cdots, FN_{k-1}, X_k \ge d_{CM}\right) \\
&=P\left(TN_1\right) \cdot P\left(TN_2 \mid TN_1\right) \cdots P\left(TN_{k-1} \mid TN_{k-2}\right) \\
&\cdot P\left(X_k \ge d_{CM} \mid TN_{k-1}\right) \\
&+\sum_{i=1}^{k-1}\left\{P\left(TN_1\right) \cdot P\left(TN_2 \mid TN_1\right) \cdots P\left(TN_{i-1} \mid TN_{i-2}\right)\right. \\
&\cdot P\left(FN_i \mid TN_{i-1}\right) \cdot P\left(FN_{i+1} \mid FN_i\right) \cdots P\left(FN_{k-1} \mid FN_{k-2}\right) \\
&\left.\cdot P\left(X_k \ge d_{CM} \mid FN_{k-1}\right)\right\}
\end{aligned} \tag{10}
$$

Furthermore, the expected cycle length and cost for this case 1 can be obtained by:

$$
E\left(L_1; T_{SF}\right)=T_{SF} \tag{11}
$$

$$
E\left(C_1; T_{SF}\right)=(k-1) C_{II}+C_{CM} \tag{12}
$$

Case 2: The renewal cycle ends up with CM for hard failure.

In this case, hard failure occurs before soft failure. Therefore, the actual degradation level at T_{HF} does not exceed d_{CM}. And according to whether there is FN, the degradation path of this case can further be divided into three subcases:

(1) The actual degradation level at the l^{th} inspection time does not exceed d_{PM}, where $l=\lfloor T_{HF}/\tau \rfloor$ is the number of inspections before the hard failure time T_{HF};

(2) At time interval $\left[(i-1)\tau, i\tau\right], i \le l$, the actual degradation level first exceeds d_{PM} but not exceeds d_{CM}, and FNs occur for the i^{th} to the l^{th} inspections.

Therefore, on condition of given $T_{HF} \in (0,+\infty)$, the probability of case 2 is:

$$P_2(T_{HF}) = P\{TN_l\} + \sum_{i=1}^{l} P\{TN_1, \cdots TN_{i-1}, FN_i, \cdots, FN_l\}$$
$$= P\{X(l\tau) < d_{PM}\}$$
$$+ \sum_{i=1}^{j-1} \{P(TN_1) \cdot P(TN_2 | TN_1) \cdots P(TN_{i-1} | TN_{i-2})$$
$$\cdot P(FN_i | TN_{i-1}) \cdot P(FN_{i'} | FN_{i-1}) \cdots P(FN_l | FN_{l-1})\} \quad (13)$$

Furthermore, the expected cycle length and cost for this case 3 can be obtained by:

$$E(L_2; T_{HF}) = T_{HF} \quad (14)$$

$$E(C_2; T_{HF}) = lC_{II} + C_{CM} \quad (15)$$

Case 3: The renewal cycle ends up with inspected PM.

In this case, the magnitude of arrived shocks before the j^{th} inspection time $j\tau$ are no larger than d_{HF}. And according to whether there is FN or FP, the degradation path of this case can further be divided into three subcases:

(1) At time interval $[(i-1)\tau, i\tau], i < j$, the actual degradation level first exceeds d_{PM} but not exceeds d_{CM}, and FNs occur for the i^{th} to the $(j-1)^{th}$ inspections;

(2) At time interval $[(j-1)\tau, j\tau]$, the actual degradation level first exceeds d_{PM} but not exceeds d_{CM}, and this is truly inspected at the same time;

(3) At the j^{th} inspection time $j\tau$, the actual degradation level does not exceeds d_{PM}, but there is an FP.

Therefore, for $j = 1, 2, \cdots, +\infty$, the probability of this case is:

$$P_3(j) = P_3^D(j) \cdot P_3^H(j) \quad (16)$$

where $P_3^D(j)$ is the probability for the degradation path before $j\tau$, and $P_3^H(j)$ is the probability of no hard failure by $j\tau$:

$$P_3^D(j) = \sum_{i=1}^{j-1} P\{TN_1, \cdots TN_{i-1}, FN_i, \cdots, FN_{j-1}, TP_j\}$$
$$+ P\{TN_1, \cdots TN_{j-1}, TP_j\} + P\{TN_1, \cdots TN_{j-1}, FP_j\}$$
$$= \sum_{i=1}^{j-1} \{P(TN_1) \cdot P(TN_2 | TN_1) \cdots P(TN_{i-1} | TN_{i-2})$$
$$\cdot P(FN_i | TN_{i-1}) \cdots P(FN_{j-1} | FN_{j-2}) P(TP_j | FN_{j-1})\}$$
$$+ P(TN_1) \cdot P(TN_2 | TN_1) \cdots P(TN_{i-1} | TN_{i-2}) \cdot P(TP_j | TN_{j-1})$$
$$+ P(TN_1) \cdot P(TN_2 | TN_1) \cdots P(TN_{i-1} | TN_{i-2}) \cdot P(FP_j | TN_{j-1}) \quad (17)$$

$$P_3^H(j) = \sum_{r=0}^{+\infty} \left\{ [F_W(d_{HF})]^r P[N(j\tau) = r] \right\}$$
$$= \sum_{r=0}^{+\infty} \left\{ [F_W(d_{HF})]^r (\lambda_0 j\tau)^r e^{-\lambda_0 j\tau} / r! \right\} \quad (18)$$

Furthermore, the expected cycle length and cost for this case 3 can be obtained by:

$$E(L_3; j) = j\tau \quad (19)$$

$$E(C_3; j) = jC_{II} + C_{PM} \quad (20)$$

Based on the derived results for cases 1, 2 and 3, we can obtain that

$$E[L] = \int_0^{+\infty} E(L_1; T_{SF}) \cdot P_1(T_{SF}) d[F_{SF}(t)]$$
$$+ \int_0^{+\infty} E(L_2; T_{HF}) \cdot P_2(T_{HF}) d[F_{HF}(t)]$$
$$+ \sum_{j=1}^{+\infty} E(L_3; j) \cdot P_3(j) \quad (21)$$

$$E[C(L)] = \int_0^{+\infty} E(C_1; T_{SF}) \cdot P_1(T_{SF}) d[F_{SF}(t)]$$
$$+ \int_0^{+\infty} E(C_2; T_{HF}) \cdot P_2(T_{HF}) d[F_{HF}(t)]$$
$$+ \sum_{j=1}^{+\infty} E(C_3; j) \cdot P_3(j) \quad (22)$$

where $F_{SF}(t)$ and $F_{HF}(t)$ is respectively the CDFs of T_{SF} T_{HF}:

$$F_{SF}(t) = P\{T_{SF} < t\} = P\{X(t) > d_{SF}\} = F_X(d_{SF}; t) \quad (23)$$

$$F_{HF}(t) = P\{T_{HF} < t\} = \sum_{r=0}^{+\infty} \left\{ [F_W(d_{HF})]^r P[N(t) = r] \right\} \quad (24)$$

Therefore, the long run cost rate for the CBM strategy with imperfect inspections can be calculated by the ratio of $E[C(L)]$ and $E[L]$. And through minimizing the cost rate, we can obtain the optimal τ and d_{PM}.

TABLE II. MODEL PARAMETER VALUES FOR THE GIL

Parameter	Value	Sources
α	1/12	[8]
β	1/6	[8]
σ_ε	3	Assumption
d_{SF}	15	[8]
λ_0	6.1033	[8]
μ_W	2703.8019	[8]
σ_W	88.2624	[8]
d_{HF}	2980	[8]
C_{II}	8	Assumption
C_{PI}	10	[8]
C_{PM}	30	Assumption
C_{CM}	50	[8]

V. NUMERICAL EXAMPLE

In this section, the proposed CBM strategy with imperfect inspections is illustrated with a numerical example of the GIL. According to the statistical analysis results in [6], parameters concerning the degradation process, arrival of random shocks, and the perfect inspection and maintenance cost are listed in Table II. Besides, we have also made proper assumptions for the standard deviation of the normally distributed inspection error, and also the cost for each imperfect inspection.

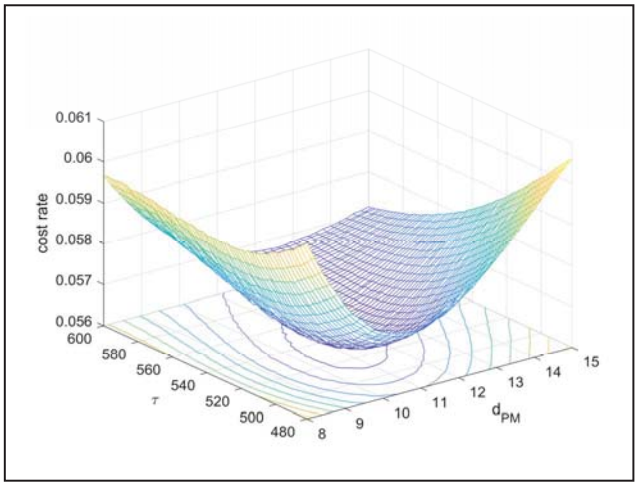

Figure 2. Maintenance cost rate with respect to τ and d_{PM}

Based on the derived results in Section IV, the long run cost rate can be computed for any maintenance strategy with given τ and d_{PM} . In Fig. 2, we plot the shape and the iso-level curves for the maintenance cost rate with respect to $\tau \in [480, 600]$ and $d_{PM} \in [8, 15]$. It can be seen that the surface is convex, and an optimal combination of the inspection and maintenance policy is found to be $\tau = 534$ and $d_{PM} = 11$, corresponding to the minimum cost rate $C_\infty = 0.0562$.

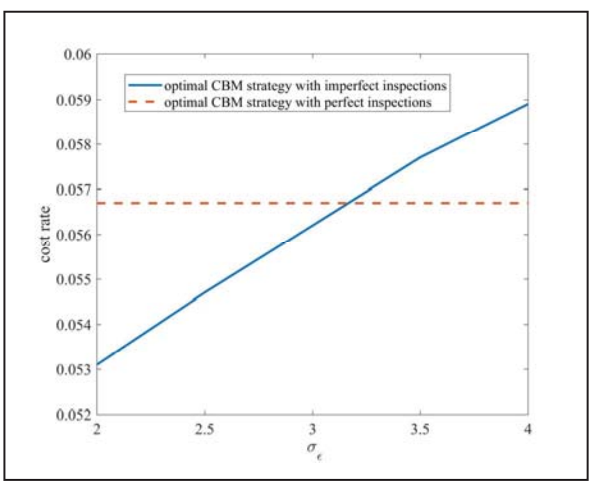

Figure 3. Sensitivity analysis of the optimal maintenance cost rate to σ_ε

Furthermore, to investigate the effect of imperfect inspections on the CBM strategy, we also conduct sensitivity analysis of the optimal maintenance cost rate to σ_ε and C_{II} , respectively shown in Fig. 3 and Fig. 4. It can be seen that with the increase of either σ_ε or C_{II} , the optimal cost rate of the proposed CBM maintenance strategy shows an obvious rising trend. Besides, by comparing the CBM strategy with imperfect inspections and that with perfect inspections, we can find that for the GIL with either low imperfect inspection cost or small inspection error, properly designing the CBM strategy with imperfect inspections can obtain better economic performance.

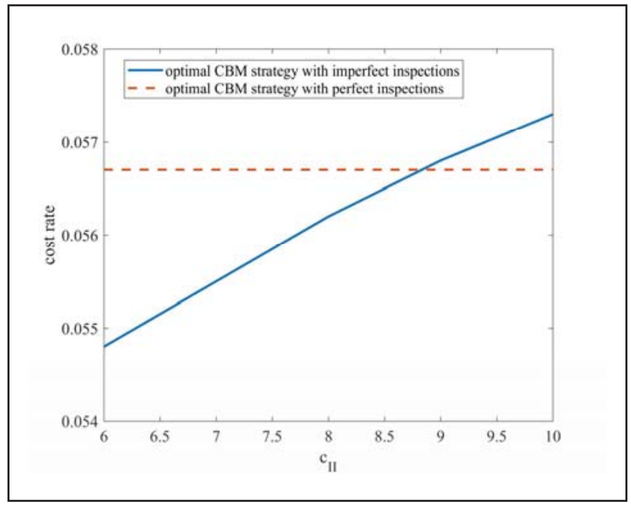

Figure 4. Sensitivity analysis of the optimal maintenance cost rate to C_{II}

VI. CONCLUSION

Taking into account the impacts of imperfect inspections, this paper presents a new CBM strategy for the GIL subject to competing failure processes of continuous degradation and random shocks. Possibilities of both FP and FN are accounted for the cost analysis of the maintenance strategy. To be specific, the long run cost rate is calculated in three cases: the renewal cycle ending up with CM for soft failure, CM for hard failure, or PM. By minimizing the long run cost rate, the optimal inspection and maintenance strategy can be designed with two decision variables, i.e., inspection interval τ and preventive maintenance threshold level d_{PM} . Finally, a numerical example of the GIL is provided to illustrate the effectiveness of the proposed CBM strategy with imperfect inspections. It can be concluded that compared to the CBM with perfect inspections, the proposed strategy with imperfect inspections can lead to higher economic efficiency, as long as the imperfect inspection cost is not too high, or the variance of the inspection error is not too large.

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