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Reliability evaluation of different scenarios of planned replacement and imperfect periodic inspection

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***Résumé* – Les réseaux électriques étant de plus en plus interconnectés, les unités de production se détériorent plus rapidement en raison de la fatigue, et d'autres mécanismes de dégradation, ce qui entraîne une réduction de leur durée de vie et des remplacements non planifiés coûteux. Pour prolonger la durée de vie d'un système multi-états, il est essentiel de les inspecter fréquemment et de les réparer en cas de dommage partiel, ce qui est appelé dans cet article "Inspection Périodique (IP)". En outre, un "Remplacement Planifié (RP)" peut également prévenir les coûteux remplacements non planifiés. Dans cet article, différentes fréquences de IP et PR sont discutées et leur impact sur la disponibilité et les coûts du système est évalué. En outre, deux scénarios de RP sont évalués afin de déterminer le moment optimal pour le remplacement du système en fonction du coût et de la disponibilité du système.**

***Abstract* – As power grids become increasingly interconnected, generating units deteriorate more rapidly due to fatigue, wear, and other degradation mechanisms, resulting in shorter service lives and costly unplanned replacements. To extend the lifespan of a multi-state system, it is essential to inspect them frequently and repair them if any partial damage is found, which is called in this paper "Periodic inspection (PI)". Moreover, a "Planned Replacement (PR)" can also prevent costly non-planned replacements. In this paper, different frequencies of PI and PR are discussed and their impact on system availability and system costs is evaluated. In addition, two scenarios of PR are evaluated to determine the optimal time for system replacement based on the cost and system availability.**

***Mots clés* - Système multi-états, Maintenance, Fiabilité, Chaînes de Markov**
***Keywords* – Multi-state system, Maintenance, Reliability, Markov chains**

1 INTRODUCTION

Most of the time, the condition of a system can vary among different values rather than only two states (perfect functioning and complete failure). Practical circumstances can be oversimplified if a binary state reliability definition is assumed. In multi-state degradation systems, the system may function between a perfect state and a complete failure. Intermediate states may result from deterioration of the system or peripheral factors, a reduction in efficiency, failure of non-essential components, and random shocks [1]. In general, systems or components deteriorate over time, and their failure rates are typically represented by a bathtub-shaped curve. Aging is defined as a phenomenon of increasing failure rate with the passage of time (age). If the risk of failure is not increasing with age, then there is no aging in terms of reliability theory, even if the calendar age of a system is increasing [2].

In order to maintain a degraded and aging system at a desired level of reliability, maintenance is critical. Generally, there are two types of maintenance: Corrective Maintenance (CM) and Preventive Maintenance (PM) [3]. CM is required when a component fails completely. Planned Replacement (PR) is also performed to prevent the system from ending up in a sudden failure with catastrophic and costly consequences and an expensive PM. In contrast, PM involves the systematic inspection of equipment where potential problems are detected and corrected in order to prevent equipment failure and increase system lifetime. There are three main types of preventive maintenance: time, usage, and condition-based triggers [4]. A very popular choice of PM is called “Periodic Inspection (PI)”, which is a mix of PM and CM. Let's say you perform a periodic inspection on a system every five years. During one of these inspections, you find that some components have been damaged, so you replace or repair them. This is an example of PI, which is being performed in many generation units.

Power plants generate electricity to supply the market and sells its excess output on wholesale markets. However, over time, systems and components degrade and age, resulting in a system with lower condition and performance states as well as increased failure rates [5]. Therefore, a periodic PIM and PR are essential for each generating unit. However, maintenance actions are not always able to restore a system to its "as-good-as-new" condition. If that were the case, the system might be used for an infinite period of time or an unlimited number of missions. In the degraded state, maintenance procedures can restore the system to its best performance. However, as time passes, the system will continue to age and its failure rate will continue to increase, which is referred to as "as bad as old"[5].

In this paper, a general system that experiences aging and degradation over time is considered, and some analyses of different PI with PR are provided. The system reliability is calculated based on Continuous Time Markov Chain (CTMC) and reliability evolution after each PI or PR is analyzed.

The rest of the paper is organized as follows. In Section 2, a reliability model based on Markov Chain is presented to evaluate system availability under different PI and PR. The aging system and the way of integration into the model are also discussed in Section 3. The numerical results are presented in Section 4. And finally, the conclusion is given in Section 5.

2 SYSTEM DESCRIPTION AND AVAILABILITY CALCULATIONS

In a degraded system, there may be k ($k = 1, 2, \ldots, K$) different conditions and performance states, of which k-1 are degraded states and one is a complete failure. In Markov chains for Multi-State Systems (MSS), transition rates (intensities) between states i and j are defined by the corresponding system failure λ_{ij}. State K denotes that the system is in perfect condition and working. Upon degradation, the system can fall into the second deterioration state, which is characterized by a lower condition or level of performance. As a result of degradation, the system state will transit subsequently to the next condition state (a lower state) and eventually to the failure state. However, Power plants are maintained in good condition by performing a PI. When a PI arrives, the system will be analyzed, and it will be repaired if any damage is found in the system. In other words, the system condition returns to its initial performance level. However, due to aging, the transition rate (λ_{ij}) among states will increase over time. Aging can be indicated by any failure rate that may be increasing as a function of time $(\lambda_{ij}(t))$ [1]. We refer to this type of maintenance as “Imperfect Periodic Inspection (IPI). Imagine a generator that, after every maintenance, returns to its best condition and performance. The degradation will, however, occur more quickly than before and a more frequent IPI is needed to maintain availability. In the case of having periodic maintenance, accelerated degradation (aging) would result in costly maintenance or the loss of the system before maintenance is due. Figure 1. (a) presents the state transition diagram of a system with degraded states: perfect, good, poor, and a complete failure state. Figure 1. (b) also shows the increase in transition rates $(\lambda_{ij}(t))$ among states as the system ages and causes a tendency toward more frequent partial or final failures [3]. To include aging in the proposed model, we suppose the system lifetime is partitioned into some small intervals, where for each time interval, the failure rate may be assumed to be constant. The aging system’s failure rate can be expressed as follows:

$$\lambda_{ij}(t+\Delta t) = \lambda_{ij}(t) + Pr_{o,ss}\big((n-1)\Delta t\big)\alpha_{ij} \qquad j = i-1 \tag{1}$$

where α_{ij} represents an increase in value of the transition rates from state i to j. The coefficient $Pr_{o,ss}\big((n-1)\Delta t\big)$, ranging from 0 to 1, depends on the duration of exploitation and the frequency of start/stop events within the previous interval. Δt represents the time interval duration. N represents as the number of intervals that partition the system lifetime T. The length of each interval is $\Delta t = T/N$. The failure rate $\lambda_{ij}(t)$ in each time interval $[\Delta t(n-1), \Delta t(n)]$, $1 \le n \le N$, can be approximated by a constant value, which represents the value of $\lambda_{ij}(t)$ at the end of the corresponding nth time interval. Note that the higher the α_{ij}, the faster a system ages.

In regard to $Pr_{o,ss}$, Table 1 provides a classification of various exploitations and number of start/stop events in each interval to compute the coefficient of increase in failure rate for that interval. The $Pr_{o,ss}$ total will be calculated as the average of both start/stop (Pr_{ss}) and percentage of exploitation during the interval (Pr_o). Keep in mind that if the coefficient values for each interval are high, it indicates a higher failure rates for the following intervals. These values of Pr_{ss} and Pr_o can be coupled to physical-based degradation and prognosis models (e.g. [6,7]) and to simulate future exploitation of the different units.

Table 1. The grouping of different exploitation and start/stop events

Operations time (% of interval)	Pr_o	Numbers of Start/Stop	Pr_{ss}
1-10	0,20	1-100	0,20
10-40	0,40	100-400	0,50
40-80	0,80	400-1200	0,80
80-100	1,00	>1200	1,00

A continuous-time Markov chain (CTMC) can be used to describe a system's state given the matrix of transition intensities [8]. To determine the probabilities of a system's states, Chapman-Kolmogorov equations must be solved. The matrix of transition intensities (Q) of the CTMC model is described below:

$$\boldsymbol{Q} = \begin{bmatrix} \boldsymbol{D} & \boldsymbol{d} \\ 0 & 0 \end{bmatrix} \tag{2}$$

Where D represents the transient states among degraded states and d expresses the absorbing states. Moreover, the general form of the infinitesimal generator matrix is:

$$\boldsymbol{Q} = \begin{bmatrix} -\lambda_{12} & \lambda_{12} & & & & \\ & -\lambda_{23} & \lambda_{23} & & & \\ & & \ddots & \ddots & & \vdots \\ & & & -\lambda_{k-2,k-1} & \lambda_{k-2,k-1} & \\ & & & & -\lambda_{k-1,k} & \lambda_{k-1,k} \\ & & \boldsymbol{0} & & & 0 \end{bmatrix} \tag{3}$$

It is worth emphasizing that the last column of the matrix describes the absorbing state and system breakdown. The following differential equations can be used to find the state probability of ith state (P_i^n) at the end of each time interval:

$$\frac{dP_i^n(t)}{dt} = \left(\sum_{i=1}^{K} P_i^n(t)\lambda_{ij}^n\right) - P_i^n(t)\sum_{i=1}^{K}\lambda_{ij}^n \tag{4}$$

where K is the number of states and λ_{ij} is the intensities of transitions from state i to state j which are defined based on corresponding failure rates on time interval n. After each ICPM, system returns to the first state. Therefore, the initial conditions for equation 4 for the first time interval after each ICPM (n_{icpm}) are as follows:

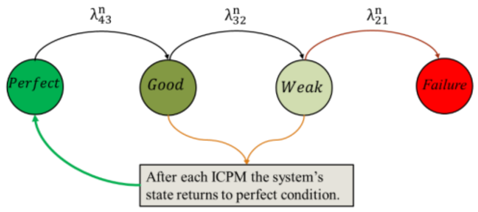
$$P_K^{n_{icpm}}(0) = 1, P_{K-1}^{n_{icpm}}(t) = 0, \ \dots \ , P_1^{n_{icpm}}(t) = 0 \tag{5}$$

For any other time intervals, the initial conditions for the next time interval are defined by the solutions at the end of the previous interval and are defined as follows:

$$P_i^n(0) = P_i^{n-1} \qquad i = 1, 2, 3, \dots K\,; \\ n = 1, 2, 3, 4 \dots\dots N\,;\ n \neq n_{icpm} \tag{6}$$

Finally, the system reliability under each interval time n is determined as the summation of the probabilities of accepted states.

(a)



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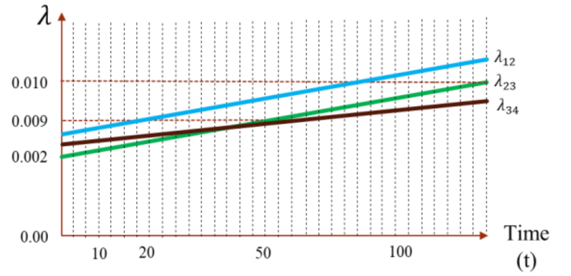


Figure 1. (a): States-transitions diagram with absorbing state, (b): Gradual increase in the transition rate by age.

3 NUMERICAL RESULTS

The system shown in Figure 1 will be examined in this section. In the first step, we will compare the availability and cost of the system under two different IPI schedules. Second, we will evaluate the risk of delaying system replacement by 50 to 75 years. Input data for this fictious example are given in Table 2. Assuming that the number of start/stop events is 450 during each interval and the operation time is 80% of each interval time, according to Table 1, the average of both factors will lead to a value of 0.9 for the $Pr_{o,ss}$. We assumed that the number of start/stop events and the operation time for all intervals remain unchanged, however, they can be treated as separate variables if there is an accurate estimation or plan for future exploitation.

3.1 Evaluation of two IPCM scenarios

The IPI frequency plays a critical role in repairable systems and should be chosen carefully. There are advantages and disadvantages to both high and low IPI frequencies. A high frequency will result in many hours of shut-down and the costs associated with unavailability. However, you keep your system as reliable as possible. In contrast, with a low IPI frequency, you would rarely stop your system to inspect and have fewer unavailability costs to pay, but you would be more likely to lose your system during its operation. We, therefore, consider two IPI scenarios, performing IPI every 4 years and every 7 years to evaluate system reliability and costs during mission time.

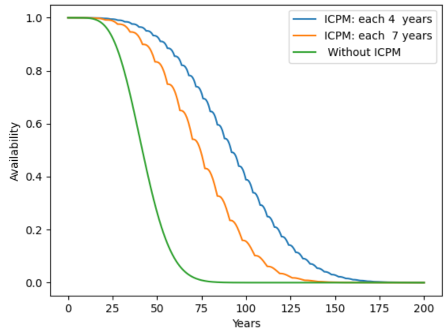
In Figure 2, two scenarios are compared in terms of availability over time. According to this figure, the frequency of 4 years could result in better availability than every 7 years. Figure 3 compares the cost of unplanned system replacement resulting from the failure state in both scenarios. Figure 4 illustrates the differences between the two scenarios with regard to the cost of unavailability due to inspection and repair of parts in degraded states. It should be noted that all costs are directly related to system availability and decrease as availability decreases. For example, IPI can be performed if the system is available. The cost of unavailability due to inspection decreases as the system availability decreases. Figure 5 shows the sum of all the costs mentioned in both scenarios as well as the difference between them. In the first 30 years, IPI performed at a frequency of 7 years would result in a lower cost than the first scenario. After this time, however, the first scenario results in a lower total cost than the second.

In terms of considering more IPI scenarios, a multi-objective optimization process is necessary to choose the best scenario. The objectives include cost and availability. Higher availability would be achieved through high-frequency IPIs. However, each IPI would incur costs related to system shutdowns and repairs. Due to page limitations, however, multi-objective optimization will be covered in future studies.

Table 2. Input data

Parameters	Value	Parameters	Value
Cost of system unavailability due to IPI (Inspection cost)	200 k$	α_{ij}	0.03
The average cost of IPI (Maintenance cost)	100 k$	λ_{43}	0.0013
Cost of Planned Replacement (PR)	8000k$	λ_{32}	0.00199
Cost of Non-Planned Replacement	18000 k$	λ_{21}	0.0000123
Pr_{ss}	450	Pr_o	85 %

(a)



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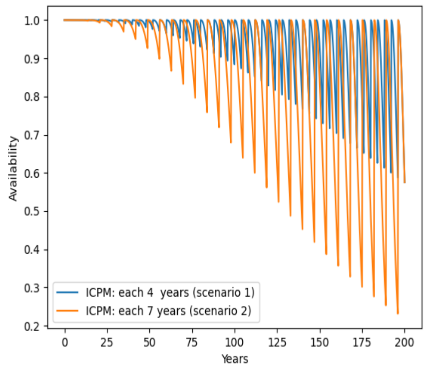
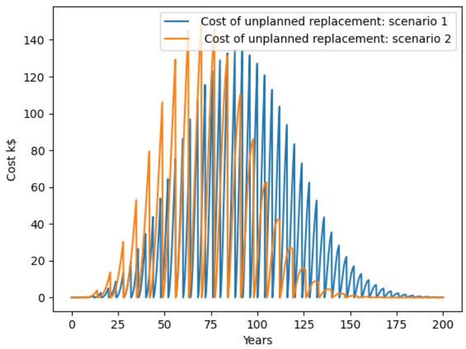


Figure 2. (a) Availability from time 0. (b) Instantaneous availability.

(a)



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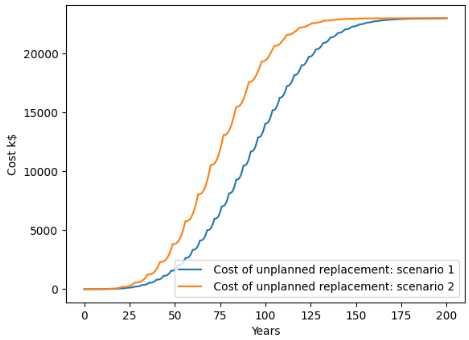
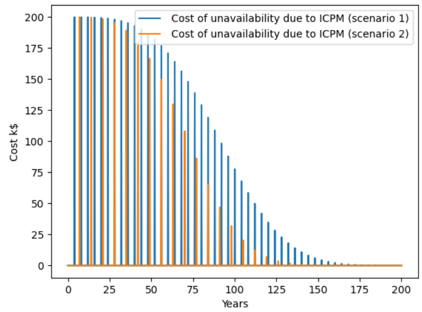


Figure 3. (a) Instantaneous cost of unplanned replacement. (b) The cumulative cost of unplanned replacement.

(a)



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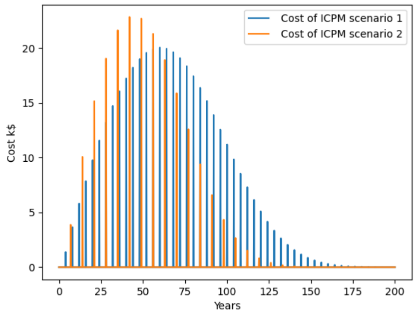


Figure 4. (a) Cost of unavailability due to IPI and (b) Cost of performing ICPM for both scenarios.

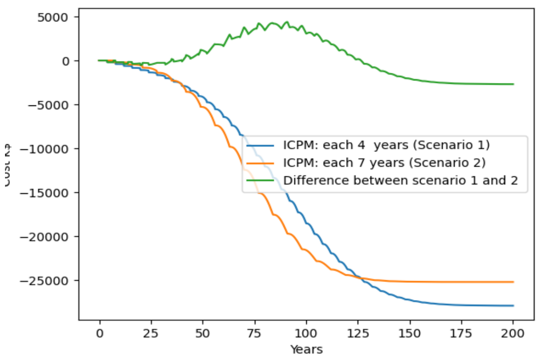


Figure 5. Total cost for both scenarios over time.

3.2 Evaluation of two Planned-Replacement (PR) scenarios

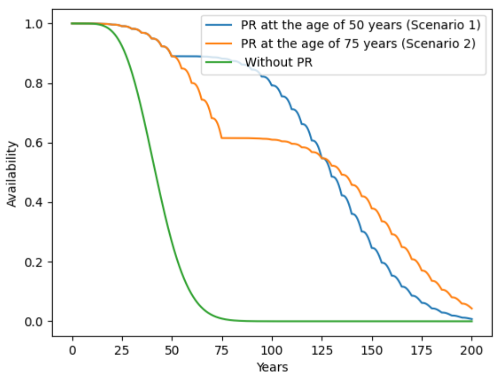
Planned replacement, or replacing an item before it fails, is mandatory for many critical parts, especially engines and engine accessories. If this policy is used appropriately, as well as safety and reliability, it can also save time, reduce costs, or produce a combination of these benefits.

A sudden failure requiring unplanned replacement will have a much higher cost than a planned replacement. In order to avoid this cost, the system needs to be replaced at the right time, neither too young nor too old. Likewise, we evaluate two PR scenarios. The system would be replaced at the age of 50 in the first scenario, and at 75 in the second scenario. Both PR scenarios used the same IPI with a frequency of 7 years.

Figure 6 illustrates the availability of the system in both scenarios. This figure shows the impact of PR on instantaneous system availability and total availability over time. Figure 7 (a) shows the cost of a sudden failure for both scenarios. Lastly, Figure 7 (b) illustrates the total cost (cost of inspection, repair, and unexpected failure) in both scenarios.

Finding the best PR scenario for the system is very dependent upon finding an acceptable availability for the system. By comparison, if the availability acceptable for the system is 0.80 by experts, it needs to be replaced at 50; any lower value would result in a replacement at 75. While combining PR with different IPI frequencies, more scenarios can be considered.

(a)



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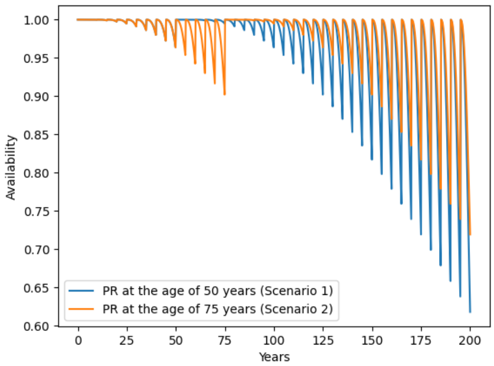
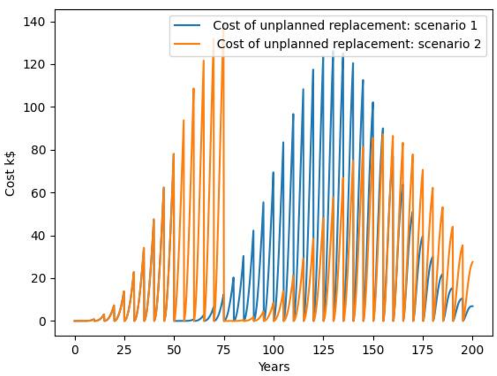


Figure 6. (a) Availability from time 0; (b) Instantaneous availability.

(a)



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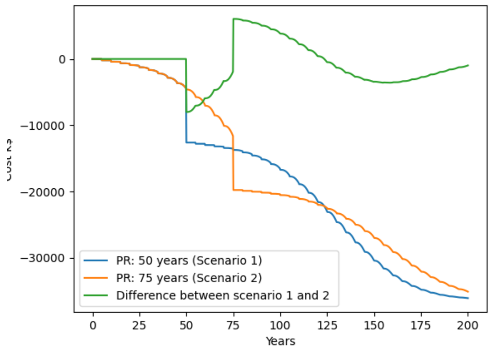

Figure 7. (a) The cost of a sudden failure for both scenarios. (b) The cumulative of the total cost (cost of inspection, repair, and unexpected failure) in both scenarios.

4 CONCLUSION

In multistate degradation systems, the system may be in its perfect state, an intermediate state, or a failure state. In order to keep such a system at a desirable level of reliability and avoid unplanned replacements, inspection and repairs, if necessary, (IPI) more frequently besides planned replacements (PR) are essential. The paper evaluated different scenarios of IPI and PR considering system availability and system cost over time. It was found that as the frequency of IPI increased, the cost would increase along with the availability. Following this, we examined different ages for PR and evaluated system availability and cost for each with the same IPI. Future studies could consider more scenarios and conduct optimization with consideration of both cost and availability by combining PR and different IPI frequencies.

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