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Performance Enhancement of Renewable Energy Systems Subject to units' Degradation and Performance Dependence

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Abstract

A performance enhancement model for multi-state renewable energy systems is introduced and developed in this paper. This model's objective is to provide a maintenance decision support, taking into account units' degradations and system interdependencies. Performance enhancement actions consider both preventive and corrective strategies and the model's thresholds are based on units' performance. The Universal Generating Function was used to assess unit performance, dependence and degradation. A case study is provided based on a simple series-parallel wind energy multi-state system, and the results show how this decision support model can be cost effective and enhance the global performance of the system. Afterwards, importance measure analysis was used to assess the performance thresholds of this model.

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Keywords: Performance enhancement; Multi-state system; Decision support; Universal Generating Function; Degradation; Dependence; Importance measure; Optimization.

1. Introduction

Extensive research has been carried out on the reliability and performance enhancement of renewable energy systems [1]. These systems are, in most cases, multi-state systems (MSS). When applied to MSS, reliability or performance enhancement is a measure of the ability of the system to provide a required performance level [2]. However, when assessing MSS performance in order to enhance it (through maintenance for instance), an

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independent MSS without any unit dependent degradation is generally assumed. This is the research gap filled in this paper. Thus, this paper covers the future works presented in our last paper [3], and presents a decision support model for MSS performance enhancement taking into account component degradation and system interdependencies. The model thresholds (for dependent and independent units) are based on units' performance. To do so, this paper relies on the universal generating function (UGF) to model unit degradation and its dependencies; thanks to a polynomial approach that allows rapid performance evaluation [3]. Finally, an importance measure model is provided as a sensitivity analysis of the decision support model (provided in the supplementary material).

This paper is structured as follows: section 2 develops the performance enhancement decision support model for the MSS. Section 3 illustrates this model through a simple series-parallel wind energy MSS. Then a final section concludes the paper and gives directions for future works.

2. Performance enhancement model

2.1. The UGF technique

The UGF is a widely used technique for MSS performance assessment. This technique is described in [4] and is represented as in equation (1):

$$u_i(z) = \sum_{k=0}^{n_i} p_{ik} \cdot z^{g_{ik}} \quad (1)$$

where:

- “ p_{ik} ” is the probability of reaching performance state “ g_{ik} ”;
- “ g_{ik} ” is the performance state “ k ” of unit “ i ”.

Levitin in [4] describes the UGF function for independent units. These units can either be set in series or in parallel.

2.2. From a degradation distribution function of a unit to its UGF function

The MSS presented in this model consists of multiple units. Every unit has multiple discrete or continuous (turned into discrete) states, distinguishable by performance or level of degradation states. For instance, a flow transmission generator in a wind turbine could have a set of different states characterized by a generated performance that could be 2 MWh, then 1.8 MWh, then 1.5 MWh and so on. The condition of the generator, its ‘health’, thus goes from “normal” working, then to “low damaged” and so on until it arrives at “complete failure/damage”.

When we consider a unit in a complex system, if its failure rate follows a Weibull distribution (2-parameter Weibull), this function would be (2):

$$f(x) = \frac{\beta}{\eta} \left(\frac{x}{\eta}\right)^{\beta-1} e^{-\left(\frac{x}{\eta}\right)^\beta} \quad (2)$$

with (β, η) as the shape and form parameters of this distribution, respectively. In order to transform this function from a continuous to a discrete form, the distribution of this unit “ i ” is divided into “ n_i+1 ” equal states. Thus, the probability of the k^{th} state is (3):

$$P_r(x_k) = \int_{(k-1)\Delta x}^{k\Delta x} f(x) \cdot dx \quad (3)$$

with:

- $\Delta x = \frac{x_{max}}{n_i+1}$ is the step size
- “ x_k ” is the expected value of performance in k^{th} state

Thus, we obtain (4):

$$x_k = \frac{k\Delta x + (k-1)\Delta x}{2} \quad (4)$$

The unit “ i ” failure rate has then been discretized in multiple states. This process is the same for other

degradation distributions such as Gaussian or Poisson. If we consider “ $P_i = p_{i0}, p_{i1}, \dots, p_{in}$ ” as the state’s probability distribution of the unit “ i ”, and “ $G_i = g_{i0}, g_{i1}, \dots, g_{in}$ ” as their corresponding performances, then we get the initial UGF function described in equation (1).

When assessing the dependencies of the renewable energy MSS, performance distribution is considered, i.e. the influence of one unit’s performance on another unit is taken into account.

2.3. MSS performance enhancement decision support

To develop such a decision support model taking into account degradation and dependency of units, we integrate corrective and preventive maintenance actions into this model. The former are activated when each unit’s state reaches the threshold state “ g_{CM} ”, and this maintenance action is considered as “As Bad As Old – ABAO” maintenance type (see equation (5)). The latter are activated when a unit reaches the threshold state “ g_{PM} ” and it renews the unit performance accordingly, this maintenance is considered as “As Good As New-AGAN” (see equation (6)) [5].

ABAO actions: Before $u_i(z) = \sum_{k=0}^{n_i} p_{ik}(t) \cdot z^{g_{ik}(t)}$ → After $u_i(z) = \sum_{k=0}^{n_i} p_{ik}(T - t) \cdot z^{g_{ik}(T-t)}$ (5)

AGAN actions: Before $u_i(z) = \sum_{k=0}^{n_i} p_{ik} \cdot z^{g_{ik}}$ → After $u_i(z) = p_{ni} z^{g_{ni}}$ (6)

where “(T, t)” are the total period and the expected ABAO action period, respectively. “ n_i ” is the perfect state.

Before carrying out every performance enhancement action, such as maintenance actions (ABAO and AGAN), MSS performance is calculated taking into account MSS dependence. This groups performance enhancement activities with the criteria of unit performance and dependency. Afterwards, in order to assess the decision support model, the following costs are considered:

- C_{fixe} : fixed maintenance costs (hourly salary, insurance...);
- C_{CM} : corrective (ABAO) costs;
- C_{PM} : preventive (AGAN) costs;
- C_{log} : maintenance setup: preparation, access, logistic...

Finally, the flowchart for the performance enhancement decision model is presented in Fig. 1.

As seen in this figure, the decision model starts by initiating system units and use UGF techniques for unit performance assessment (including degradation). Then, performance enhancement activities are performed based on the performance criteria.

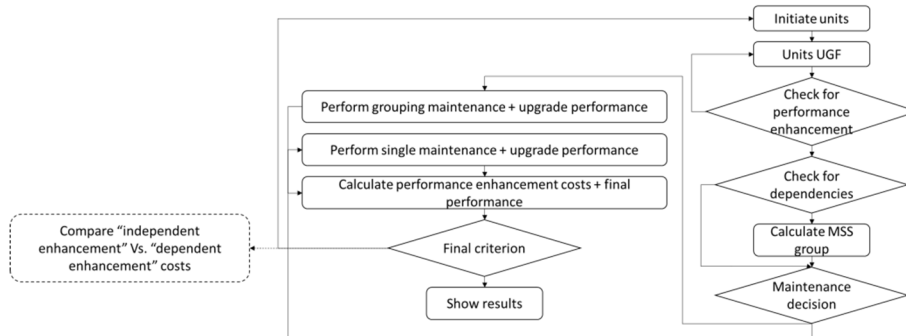


Fig. 1. Performance enhancement model flowchart. Maintenance actions are a part of performance enhancement actions.

If performance enhancement is required, the model checks for dependencies among the degraded units. After identifying unit interactions, it calculates the dependent group unit performance to check whether if a single unit maintenance or group maintenance actions should be performed. Afterwards, the total costs can be generated and the

MSS performance updated. In order to assess the effectiveness of the proposed model, we compare “dependent” and “independent” performance enhancement actions.

3. Case study

The performance enhancement decision support model is illustrated using the following MSS as a part of a wind turbine system (Fig. 2).

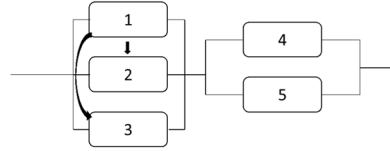


Fig. 2. Case study of the multi-state system (MSS)

The proposed MSS is composed of five units that follow a degradation process (5 different states). Units (2 & 3) are influenced by the performance of unit “1”. The performance dependencies of these units are as follows:

- if $g_1=0$, then $p_{1/2}=(0.3/0.7)$ and $p_{3/1}=(0.2/0.8)$
- if $g_1=1.2$, then $p_{2/2}=(0.7/0.3)$ and $p_{3/2}=(0.8/0.2)$

Unit performance and maintenance criteria are described in Table 1. Units (4 & 5) are independent.

For the sake of simplicity, ABAO and AGAN performance enhancement action costs are assumed to be equal.

The objective of this case study is to generate performance enhancement (maintenance) costs for 11 iterations (time windows) in case of dependency and non-dependency. Results are presented in Fig. 3 and are discussed below.

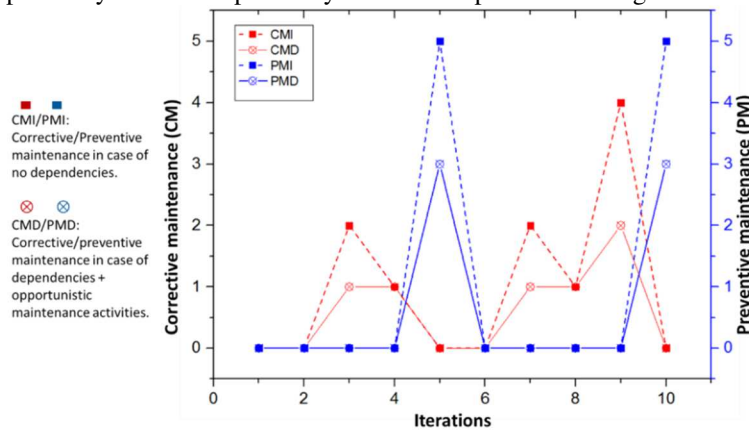


Fig. 3. Performance enhancement variations in case of dependent and independent MSS. Number of corrective actions (CM) is ABAO actions, whereas number of preventive ones (PM) is AGAN.

In the case of no dependence, for every unit, and according to each performance degradation state, the UGF performance function is calculated. The proposed model checks whether any of the units reach the AGAN or ABAO performance criteria trigger points. For instance, the first units reaching the ABAO criteria are units (3 & 4). After performing maintenance actions, the performance of these units would be upgraded from (1.6 → 1.7) and (1.3 → 1.4), respectively. Similar performance enhancements are performed when units are under AGAN actions. Maintenance costs are presented in Table 2. In case of dependency, unit “1” influences the performances of units 2 & 3. Their respective performances can be then assessed through one grouped sub-system with a renewal function. Equations and iterations to calculate the performance and UGF functions for the MSS in both these cases of dependency are described in the supplementary material presented in [5]. Performance enhancements are performed, and maintenance costs in the case of dependency are presented in Table 2. Thus, when grouping performance enhancement activities under constraints of performance sharing dependencies, corrective maintenance costs (CMD line) are reduced by $5(C_{fixe}+C_{log})$. The cost effectiveness of such actions can be seen in Fig. 3 as well as AGAN

actions (PMD line in Fig. 3). Thus, dependency can influence MSS performance and optimize its enhancement.

Table 1. Case study data.

Unit	Reliability ^{performance} (R ^P)	CM criteria “G _{CM} ”	PM criteria “G _{PM} ”
1	0.1005 ¹ ; 0.3679 ^{1.05} ; 0.5408 ^{1.1} ; 0.6471 ^{1.15} ; 0.7168 ^{1.2}	E _{CM1} =1	After 5 iterations
2	0.8274 ^{1.25} ; 0.8483 ^{1.3} ; 0.8651 ^{1.35} ; 0.8787 ^{1.4} ; 0.8901 ^{1.45}	E _{CM2} =1.3	After 5 iterations
3	0.9147 ^{1.5} ; 0.9208 ^{1.55} ; 0.9262 ^{1.6} ; 0.9309 ^{1.65} ; 0.9351 ^{1.7}	E _{CM3} =1.6	After 5 iterations
4	0.8483 ^{1.2} ; 0.8651 ^{1.25} ; 0.8787 ^{1.3} ; 0.8901 ^{1.35} ; 0.8996 ^{1.4}	E _{CM4} =1.3	After 5 iterations
5	0.9480 ^{1.80} ; 0.9506 ^{1.85} ; 0.9529 ^{1.9} ; 0.9550 ^{1.95} ; 0.9569 ^{1.2}	E _{CM5}	After 5 iterations

Table 2. Maintenance costs.

MSS configuration	Costs (ABAO)	Costs (AGAN)
Independent MSS	$ABAO = 10. C_{CM} + 10. C_{fixe} + 10. C_{log}$	$AGAN = 10. C_{PM} + 2. C_{fixe} + 2. C_{log}$
Dependent MSS	$ABAO = 2. (C_{CM1} + C_{CM2} + C_{CM3}) + C_{fixe} + C_{log}$	$AGAN = 6. C_{PM} + 2. C_{fixe} + 2. C_{log}$

4. Conclusion

A performance enhancement decision support model based on unit dependencies is presented in this paper. Performance thresholds were used to trigger suitable actions in a degraded MSS. The degradation process and the performance dependency were assessed using the UGF technique. Importance measures were used to assess the sensitivity analysis of performance thresholds and are described in the supplementary material. The general results show how grouping performance enhancement activities under the criteria of dependency and degradation can be effective as a performance enhancement decision support, and that it is a cost-effective model. To the best of our knowledge, this paper is the first attempt to consider a discrete degradation process under performance dependence for MSS maintenance policy. Future works will improve the decision support model by upgrading AGAN actions to condition monitoring maintenance activities. Another perspective is the introduction of propagation of failure dependence, since it is one of the most crucial dependencies that must be taken into account when dealing with performance enhancement activities of an MSS.

Acknowledgments

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