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Maintenance policies for energy systems subject to complex failure processes and power purchasing agreement

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ABSTRACT

Power purchase agreement (PPA) has emerged as a new support contracting approach and received much attention in recent years. In this paper, a novel maintenance model under PPA is developed for a complex energy generation system, whose objective is to maximize the expected net revenue of energy suppliers. The energy system undergoes two competing and dependent failure processes, namely, soft failure process and hard failure process. The former reduces the production rate of the system, whereas the latter immediately causes the stoppage of the system. The dependence is characterized by the random increment of soft/hard hazard rate due to the occurrence of hard/soft failures. The system is minimally repaired upon a hard failure or the detection of a soft failure. Additionally, a preventive replacement is immediate when the system operational age attains the pre-determined age. The target of this article is to maximize the expected net revenue of energy suppliers via the optimization of the inspection interval and number. A case study on wind turbine system (WTS) is provided to validate the effectiveness of the adopted profit-centric approach.

1. Introduction

In recent years, power purchase agreement (PPA) has been widely used in the management of wind farms. By the end of 2014, the total number of wind farms signing PPAs has reached 363, and the total capacity is 32,641 MW (e.g., Lei & Sandborn, 2018). Bruck, Sandborn, and Goudarzi (2018) conducted a thorough literature review of PPAs for renewable energy systems. A power purchase agreement (PPA) is a performance-based contract for the purchase and sale of energy between an energy buyer and an energy provider. Within a PPA framework, the energy buyer determines the energy delivery limit and signs a contract with energy suppliers. The generated and delivered energy will be paid based on the agreed price schedule (e.g., Bruck et al., 2018; Lei & Sandborn, 2018). Under PPA, energy service providers are often better motivated to take effective maintenance actions to improve the amount of energy production (Xiang, Zhu, Coit, & Feng, 2017). This is the case considered in our study, where a maintenance model for an energy generation system is developed within the framework of PPA.

During the contract period of PPA, power plants/devices usually undergo complex failure processes due to their complex structures and harsh environmental suffered (e.g., Levitin, Zhang, & Xie, 2006; Zheng, Zhou, Zheng, & Wu, 2016; Qiu, Cui, & Gao, 2017; Qiu, Cui, Shen, & Yang, 2017; Wang, Zhao, Guo, & Li, 2018; Zhao, Guo, & Wang, 2018). Substantially, failure processes of industrial systems can be classified into two categories, namely, hard failure and soft failure (e.g., Qiu, Cui & Gao, 2017; Qiu, Cui, Shen et al., 2017; Taghipour & Banjevic, 2012; Xie, Dai, & Poh, 2004). The former is generally fatal, which stops the system immediately and thus is self-announcing. In contrast, the majority of soft failures are nonfatal in that they only reduce the production output of the system.

For complex industrial systems subject to multiple failure processes, failure dependence is a common phenomenon and extensively reviewed in literature (e.g., Lai & Xie, 2006; Liu, Wu, & Xie, 2015; Yang, Ma, Peng, Zhai, & Zhao, 2017; Yang, Ma, & Zhao, 2017). In early studies Murthy and Nguyen (1985), summarized three different types of failure interaction for a two-component system from the perspective of both failure probability and hazard rate. Recent works concentrated mainly on failure interaction between soft and hard failures. Among them, the impact of hard failure on soft failure, i.e., hard-to-soft dependence (e.g., Jiang, Feng, & Coit, 2012; Rafiee, Feng, & Coit, 2014; Yang, Ma, Peng et al., 2017; Yang, Ma & Zhao, 2017) was addressed the most. For instance, in degradation-threshold-shock (DTS) models, external shocks will accelerate the degradation process via causing a certain amount of degradation increment. In contrast, soft-to-hard dependence is rarely addressed. In existing literatures Yang, Zhao, Peng, and Ma (2018), investigated the impact of degradation level on hazard rate of fatal

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Nomenclature

Acronyms

PPA	Power Purchase Agreement
WTS	Wind Turbine System
$\lambda_s(t)$	hazard rate of soft failure in a baseline environment
$\widetilde{\lambda}_s(t)$	random hazard rate of soft failure in the presence of hard failures
$N_h(t)$	number of hard failures by time t
W_i	hazard rate increment of soft failure due to the ith hard failure
X_s	random time to a soft failure
$R_s(t)$	reliability function of X_s
$f_s(t)$	density function of X_s
$\lambda_h(t)$	hazard rate of hard failure in a baseline environment
$\widetilde{\lambda}_h(t)$	random hazard rate of hard failure in the presence of soft failures
γ	hazard rate increment of hard failure due to soft failure
L	period of PPA
R	revenue of energy supplier
R_N	net revenue of energy supplier
Q	total energy production
$Q_{\min}$	minimum energy delivery limit defined in PPA
$Q_{\max}$	maximum energy delivery limit defined in PPA
C	total maintenance cost
d_0	production rate before the arrival of a soft failure
d_1	production rate after the arrival of a soft failure
c_{m_s}	cost of a minimal repair of a soft failure
c_{m_h}	cost of a minimal repair of a hard failure
c_r	cost of a replacement
c_I	cost of an inspection
T	inspection interval
n	replacement limit
m	number of renewal cycles over the period of PPA
Q_i	energy delivery in the ith cycle
$F_{Q_i}(q)$	distribution function of Q_i
$F_Q(q)$	distribution function of Q
$Q_{((k-1)T,kT)}$	energy delivery in the kth inspection interval
X_{s_k}	working time before a soft failure arrives in the kth inspection interval
F_{s_k}	distribution function of X_{s_k}
$F_{Q_1}^{(m)}(q)$	m-fold convolution of $F_{Q_1}(q)$

shock, and accordingly formulated reliability and maintenance models.

It is worth noting that the majority of the above-mentioned studies have considered only one category of failure dependence. This may be restrictive or insufficient in characterizing complex failure behaviors. In practice, maintainers can usually observe the following fact: (1) hard failures will accelerate the deterioration speed of the system; (2) during the soft failure state, a system is much more susceptible to hard failure. Furthermore, the failure interaction between hard and soft failure is mainly investigated in the framework of DTS models. Nevertheless, the deterioration characteristics of many power generation devices are difficult to obtain, and maintenance for such devices are generally reliability-centered based on the hazard rate information. This motivates us to investigate both soft-to-hard and hard-to-soft dependence from the perspective of hazard rate. Moreover, in contrast with the maintenance model in Cha, Finkelstein, and Levitin (2017), the hazard rate increment due to each failure (either hard or soft) is a random variable instead of a constant, which is more common in actual industrial application.

Under the power purchase agreement, this paper investigates the reliability characteristics and maintenance strategy for an energy supply system. Two mutually dependent failure processes are incorporated into the reliability model, where the effect of a hard (soft) failure on the soft (hard) failure process is reflected by an abrupt jump of its hazard rate. The impact of soft failure is directly reflected by the reduction of energy production rate. Minimal repairs are performed to remove types of failures and rectify the system back to the normal state, and a preventive replacement is performed upon a certain number of inspections. The objective of this paper is to maximize the expected net revenue of energy sellers over the finite time horizon stipulated by the power purchase agreement.

The optimization objective of most maintenance models is the average long-run cost rate, which equals the expected cost in a renewal cycle divided by the expected length of a renewal cycle. Such maintenance models are applicable when the system lifecycles are infinite. Nevertheless, under the PPA, the duration of a contract for a power generation device is always finite (e.g., Bruck et al., 2018; Lei & Sandborn, 2018), and hence the steady state assumption is no longer applicable. Finite time maintenance is less investigated in literature due to its analytical and computational difficulty (e.g., Golmakani & Moakedi, 2012). When the maintenance cost and production revenue are simultaneously modeled and optimized within a finite duration, the problem becomes more mathematically involved. It inspires us to design an effective and concise algorithm for the calculation of the expected net revenue.

The proposed model is illustrated by a case study on a WTS. WTS is chosen due to the following two reasons: (1) multiple dependent failure modes are common in WTS and the corresponding research is of theoretical and practical interest to WTS owners (e.g., Abdollahzadeh, Varela, Atashgar, & Putnik, 2015; Ding & Tian, 2012; Qiu, Cui & Gao, 2017; Qiu, Cui, Shen et al., 2017; Tian, Jin, Wu, & Ding, 2011; Yang, Ma, Zhai, & Zhao, 2016); (2) PPA has emerged as a new service paradigm for the maintainers of WTS and of great potential in the future (e.g., Bruck, Goudarzi, & Sandborn, 2016; Jin, Ding, Guo, & Nalajala, 2012; Lei & Sandborn, 2018).

The main contribution of this paper is as follows.

- Developing a novel maintenance model incorporating two dependent failure processes under the framework of PPA.
- Characterize the failure interaction via the random hazard rate increment.
- Designing a multi-level maintenance strategy to deal with complex failures.
- Providing a case study on wind turbine system (WTS) to validate the application of the maintenance model.

The remainder of the paper is organized as follows. In Section 2, we review corresponding literatures about failure interaction between different failure modes and the definition of power purchase agreement. Section 3 introduces the stochastic failure model based on dependent failure modes and maintenance policy within the framework of PPA. Section 4 derives the recursive equations for the reliability of the system. Section 5 discusses the optimal inspection policy maximizing the expected net revenue of power suppliers. A numerical example of WTS is presented in Section 6 for illustration. Conclusion and future research directions are provided in Section 7.

2. Literature review

2.1. Failure interaction

Failure interaction is extensively reviewed in reliability and maintenance modeling of multi-component systems and/or systems with