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Optimization of predetermined standby mode transfers in 1-out-of-N: G systems ☆

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ABSTRACT

Warm standby redundancy is an important fault-tolerant design technique for improving the reliability of many systems used in life-critical or mission-critical applications. Traditional warm standby models aim to reduce the operational cost and failure rate of the standby elements by keeping them partially powered and partially exposed to operational stresses. However, depending on the level of readiness of a standby element, significant restoration delays and replacement costs can be incurred when the standby element is needed to replace the failed online element. To achieve a balance between the operation cost of standby elements and the replacement costs, this paper proposes a new warm standby model with scheduled (or time-based) standby mode transfer of standby elements. In particular, each standby element can be transferred from warm standby mode to hot standby mode (a mode in which the standby element is ready to take over at any time) at a fixed/predetermined time instants after the mission starts. To facilitate the optimal design and implementation of the proposed model, this paper first suggests a new algorithm for evaluating the reliability and expected mission cost of 1-out-of-N: G system with standby elements subject to the time-based standby mode transfer. The algorithm is based on a discrete approximation of time-to-failure distributions of the elements and can work with any type of distributions. Based on the suggested algorithm the problem of optimizing transfer times of standby elements to the hot standby mode and optimal sequencing of their transfer to the operation mode is formulated and solved. In this problem the expected mission cost associated with elements' standby and operation expenses and mode transfer expenses is minimized subject to system reliability constraint. Illustrative examples are provided.

1. Introduction

Using standby redundancy to improve the reliability of a system has become a well-known principle in the reliability engineering field (Johnson, 1989). Examples of applications include power systems, satellite systems, aerospace systems, telecommunication systems, distributed computing systems, etc. (ANSI/IEEE 446-1995, 1995; Coit, 2003; Pandey, Jacob, & Yadav, 1996; Pham, Phan, & Amari, 1995; Yun & Cha, 2010). The standby redundancy technique is especially important or essential for systems used in life critical or mission critical applications, such as flight control and space missions where repairing/replacing a failed element through online or onboard manual intervention is difficult or even impossible (Amari & Dill, 2010; Sinaki, 1994; Sklaroff, 1976).

According to failure characteristics and operation cost associated with an element in the standby mode, standby redundancy is classified as hot, cold, and warm (Johnson, 1989; She & Pecht, 1992). Warm standby redundancy is the most generic format while the other two types are special cases of the warm standby model (Papageorgiou & Kokolakis, 2010; Ruiz-Castro & Fernández-Villodre, 2012; Tannous, Xing, & Dugan, 2011). In a warm standby system, an element while in the standby mode is partially powered and partially exposed to operational stresses, thus the operation cost and failure rate of a warm standby element are lower than

Abbreviations: *Cdf*, cumulative distribution function; *pdf*, probability density function; *pmf*, probability mass function; *r.v.*, random variable; GA, genetic algorithm; CEM, cumulative exposure model; WSM, warm standby mode; HSM, hot standby mode; OM, operation mode.

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Nomenclature

N	number of elements in the system
$s(i)$	index of ith element in ordered sequence
T_j	*r.v.* representing the time-to-failure of element j
$p_j(i)$	probability that element j fails in time interval i after its initiation
$V_O(j)$	operation cost (per time unit) of element j
$V_W(j)$	cost (per time unit) of keeping element j in WSM
$V_H(j)$	cost (per time unit) of keeping element j in HSM
$S_{WO}(j)$	startup cost of putting element j in operation from WSM
$S_{HO}(j)$	startup cost of putting element j in operation from HSM
$S_{WH}(j)$	cost of changing WSM to HSM for element j
X_i	random working time of subsystem consisting of elements $s(1), s(2),\ldots,s(i)$: $X_i = \max_{1\leqslant j\leqslant N}(T_{s(j)})$
t_M	mission time
R	system reliability
E	expected mission cost
$Q_j(i)$	$\Pr\{X_j = \Delta i\}$
m	number of considered time intervals during the mission
Δ	duration of each time interval
$c_{s(j)}$	total cost of using element $s(j)$ during the mission
1(A)	unity function: if A = True then $1(A) = 1$; else $1(A) = 0$
$D_W(j)$	deceleration factor of element j in warm standby mode
$D_H(j)$	deceleration factor of element j in hot standby mode
t_O	random time when element should be transferred to OM
t_H	fixed time when element should be transferred to HSM
t_F	random time when element fails or is switched off
i_O	random time interval in which element should be transferred to OM
$i_H(j)$	fixed time interval in which element j should be transferred to HSM
i_F	random time interval in which element fails or is switched off
τ_{WSM}	random time element spends in WSM
τ_{HSM}	random time element spends in HSM
τ_{OM}	random time element spends in OM
t^*	cumulative exposure time of an element

those of the online active element(s) (Amari, Pham, & Misra, 2012; Li, Yan, & Zuo, 2009; Mathur, 1971; Wang, Dong, & Ke, 2006; Zhang, Xie, & Horigome, 2006). However, replacement of failed elements by warm standby elements is usually associated with considerable restoration delays and expenses. To minimize these replacement costs, the standby elements can wait for being put in operation in hot standby mode (HSM), where the standby element works in synchrony with the online active unit and is ready to take over at any time (i.e., fast restoration) (Johnson, 1989). However, keeping standby elements in HSM increases the system mission costs as the hot standby elements consume more energy and materials than warm standby ones. In addition, the elements working in HSM are exposed to more intensive stresses than in warm standby mode (WSM), which increases their failure probability and reduces the total mission reliability. To achieve the balance between the operation cost of standby elements and the replacement costs, in this work we propose a new warm standby model with scheduled standby mode transfer of standby elements. Specifically, in contrast to the traditional warm standby model where the standby element remains in the same WSM all the time before it replaces the failed online element, in our proposed model, each standby element can be transferred from WSM to HSM at a fixed time after the beginning of the mission (time-based transfer). If the online working element fails before such transfer of the standby element, the standby element is put into operation from the WSM. If the online working element fails after such transfer of the standby element, the standby element is put into operation from the HSM. The optimal choice of the transfer time should hit the balance between the operation cost of standby elements and the replacement costs.

Consider for example an electric power generating system consisting of N power generators. Different generators can be purchased at different times and installed at different places, which makes the failure characteristics of the units as well as their operation and startup costs different (Zhang et al., 2006). The replacement of a failed generator with one being in WSM can take considerable time and cause power supply interruption or reduction of the power quality (voltage and frequency characteristics). Therefore it is preferable to keep one of the standby generators as spinning reserve (HSM). By choosing proper time of spinning reserve activation one can strike the balance between the expense associated with keeping generators in standby modes and the expense associated with replacements of failed generators.

Another example that has motivated this work is a fault-tolerant wireless sensor system used for condition sensing or object detection. To conserve the limited battery power, all the standby sensors are initially in WSM (sleeping mode). To avoid or minimize the interruption of the sensing or detection task, each standby sensor can be transferred from WSM to HSM at a pre-designed time.

Using the predetermined WSM–HSM transition schedule is very convenient as system manager can plan the resource and manpower distribution in advance which saves time and cost of standby state transitions. In automated systems the scheduled WSM–HSM transition can be realized much more easily than state based transition based on sophisticated failure monitoring and prediction methods.

In the rest of the paper, we first suggest an algorithm for evaluating mission cost and reliability of 1-out-of-N: G heterogeneous standby redundant systems for any sequence of different standby elements and any WSM to HSM transfer times with respect to time-to-failure distributions of the elements. The algorithm is based on a discrete approximation of the time-to-failure distributions of the system elements. Then the optimal standby policy is analyzed which presumes choice of sequence of putting standby elements in operation and the times of their transfer from WSM to HSM that minimize the mission cost subject to providing a desired level of system reliability.

2. The system model

The system consists of N elements with one being primary and in the operation mode (OM) at the beginning of the mission, and the remaining $N-1$ elements waiting in the WSM before being put into operation. One working element can successfully accomplish the system mission i.e. the system is 1-out-of-N: G. The overall mission fails if all elements fail before the mission time.

The standby elements are transferred to the HSM or the OM in a predetermined order. The standby element j is transferred to the HSM at a predetermined time $t_H(j)$ if at this time it is in WSM. If element j does not fail before, it is transferred from either WSM or HSM to the OM immediately after the failure of a previous