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A reliability model of a warm standby configuration with two identical sets of units

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ABSTRACT

This article presents a new reliability model and the development of its analytical solution for a warm standby redundant configuration with units that are originally operated in active mode, and then, upon turn-on of originally standby units, are put into warm standby mode. These units can be used later if a standby- turned into active-unit fails. Numerical results of an example configuration are presented and discussed with comparison to other warm standby configurations, and to Monte Carlo simulation results obtained from BlockSim software. Results show that the Monte Carlo simulation model gives virtually identical reliability value when the simulation uses a high number of replications, confirming the developed model.

1. Introduction

In large systems requiring high reliability such as spacecraft, data storage centers, and electric power distribution networks, standby redundancy configurations are widely used. In spacecraft, for example, using standby redundancy has been a common practice for a long time. Coutinho reported a standby redundant hydraulic landing gear pneumatic system in aircraft in 1965 [1]. Bachofer reported a 2-for-1 standby redundant gyro and electronics configuration for Voyager attitude control subsystem [2]. Berkery et al. reported a standby power conditioning configuration for spacecraft power subsystem [3]. Molitor and Olson reported a standby redundant ion engines configuration for satellite electric propulsion subsystem [4].

In general, there are three types of standby: cold, warm and hot standby. Many efforts have been made to develop reliability models for standby redundancy, but modeling for warm standby has been especially difficult. Early works for warm standby modeling can be found in the works of Subramanian et al. [5] and Venkatachalam [6]. A most frequently referred standby reliability model was reported by She and Pecht for a general k-out-of-n warm standby redundancy [7]. Over the years, research interests in the warm standby redundancy reliability modeling have not died down. For example, El-Damcese and Helmy studied a series system with warm standby units under Weibull distributions [8]. Zhai et al. studied a binary decision diagram-based reliability model for warm standby units subject to imperfect fault coverage [9]. Amari et al. further studied some statistical characteristics of the general k-out-of-n warm standby redundancy [10] and used the characteristics to optimize design of system redundancy [11]. Singh studied a repairable warm standby redundancy with identical standby units subject to a common cause failure [12]. And Zhang et al. further studied a repairable warm standby redundancy with two different types of standby units [13]. But even with these publications existing, developing reliability models for particular standby redundancy may still be needed in practice, especially when redundancy schemes are configured differently from what have been studied.

One particular warm standby redundant configuration that has not been studied in existing publications consists of two identical sets of different functional units on each set, one primary and the other redundant. Fig. 1 shows a graphic view of such standby configuration. This configuration can be found in real complex redundant systems, such as satellite's data handling electronics subsystems.

The following describes how the standby redundancy works:

(1) Each set (A or B) consists of identical units, with one power supply and N functional units. Neither the power supply nor the functional unit is repairable.
(2) At the beginning of a mission life, all units on Set A are operating in active mode (primary set), while all units on Set B are in standby mode (redundant set).
(3) Once a failure occurs on Set A in active mode, the power supply on Set B will be turned on, driving all available functional units on Set B into active mode.

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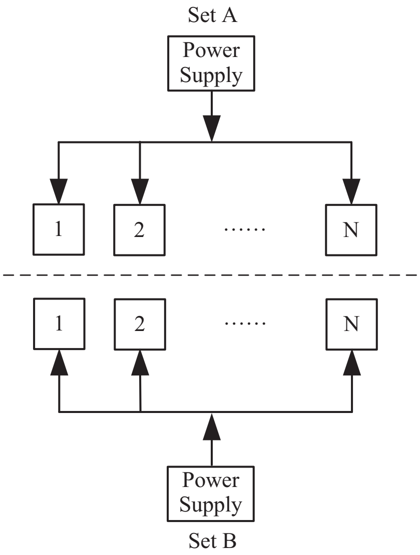

Fig. 1. Graphic view of the standby redundancy.

(4) At the same time, if there is no need for the Set A to operate, the power supply on Set A is turned off putting all surviving functional units on Set A into standby mode.
(5) Then, later on, if another failure occurs on Set B in active mode, and if the same functional unit on Set A is still available, the power supply on Set A is turned back on driving all surviving functional units on Set A back into active mode again.
(6) A mission success requires at least one of each pair of functional units to survive.

Realizing that there is no existing model that exactly matches such standby redundancy, this article presents a new reliability model for this standby redundancy with consideration for an arbitrary number of functional units. Its analytical solution is developed with closed form equations. Numerical results of an example configuration are presented and discussed with comparison to other warm standby configurations, and to Monte Carlo simulation results obtained by using BlockSim software tool.

2. Success scenarios and reliability functions

Let $\lambda_{P,A}$ and $\lambda_{n,A}$ be the failure rates of the power supply and the nth functional unit (n=1, 2, …, N) in active mode, respectively; while $\lambda_{P,S}$ and $\lambda_{n,S}$ are their failure rates in standby mode, respectively.

Assume no switching failure during turn-on or turn-off. Then, for a mission life t, a complete set of exclusive success scenarios can be described and corresponding reliability functions can be expressed as follows [14]:

(1) All units on Set A survive at time t.
For this success scenario, the reliability function can be expressed as:

$$R_1(t) = R_{P,A}(t)\cdot\left[\prod_{n=1}^{N} R_{n,A}(t)\right], \tag{1}$$

where $R_{P,A}(x)$ is the reliability function of the power supply in active mode, and $R_{n,A}(x)$ the reliability function of the nth functional unit in active mode.

(2) The power supply on Set A fails at time x ($0<x<t$). This requires that all functional units on Set A survive in active mode at least up to time x. All units on Set B, including the power supply and all functional units, survive in standby mode up to time x. The power supply is turned into active mode at time x driving all functional units into active mode which are required to survive the remaining mission in active mode.
The reliability function of this success scenario is:

$$R_2(t) = \int_0^t f_{P,A}(x)\cdot\left[\prod_{n=1}^{N} R_{n,A}(x)\right]\cdot R_{P,S}(x)\cdot\left[\prod_{n=1}^{N} R_{n,S}(x)\right] \cdot R_{P,A}(t-x)\cdot\left[\prod_{n=1}^{N} R_{n,A}(t-x)\right]\cdot dx, \tag{2}$$

where $f_{P,A}(x)$ is the probability density function of the power supply in active mode, $R_{P,S}(x)$ the reliability function of the power supply in standby mode, and $R_{n,S}(x)$ the reliability function of the nth functional unit in standby mode.

(3) One functional unit on Set A fails at time x ($0<x<t$), but before time x at least one functional unit on Set B, which is different from the one just failed on Set A at time x, already failed. This requires that the power supply and the functional unit(s) on Set A that is identical to the one(s) already failed on Set B, remains in active mode up to time t. Meanwhile, the power supply on Set B survives in standby mode up to time x, and is turned into active mode at time x, survives the remaining mission. This implies that all functional units on Set B that survive in standby mode are driven into active mode at time x, including the identical one to the failed one on Set A which is required to survive in active mode at time t.
Denote the ith functional unit on Set A fails in active mode at time x (i=1, 2, …, N).
Also denote the number of functional units on Set B that failed in standby mode before time x be M (M=1, 2, …, N-1), and the index subset of the failed units be $N_f = \{n_1, n_2, \cdots, n_M\}$. All units on Set B that are not a part of N_f are required to survive in standby mode up to time x.
Then, the reliability function of this success scenario becomes:

$$\begin{aligned} R_3(t) = \sum_{i=1}^{N}\int_0^t f_{i,A}(x)\cdot R_{P,A}(t)\cdot\left[\prod_{\substack{n=1\\ n\neq i}}^{N} R_{n,A}(x)\right] \\ \cdot R_{P,S}(x)\cdot R_{P,A}(t-x)\cdot R_{i,S}(x)\cdot R_{i,A}(t-x) \\ \times \sum_{M=1}^{N-1}\underbrace{\sum_{\substack{n_1=1\\ n_1\neq i}}^{N}\ \sum_{\substack{n_2>n_1\\ n_2\neq i}}^{N}\cdots\sum_{\substack{n_M>n_{M-1}\\ n_M\neq i}}^{N}}_{M\text{ folds}}\ \prod_{m=1}^{M}\left[1-R_{n_m,S}(x)\right] \\ \cdot\left[\prod_{\substack{n=1\\ n\neq i,n_1,n_2,\ldots n_M}}^{N} R_{n,S}(x)\right]\times\left[\prod_{s=1}^{M} R_{n_s,A}(t-x)\right] \\ \cdot\left[\prod_{\substack{n=1\\ n\neq i,n_1,n_2,\ldots n_M}}^{N} G_{2/1}(\lambda_{n,A};t-x)\right]\cdot dx, \end{aligned} \tag{3}$$

where $G_{2/1}(\lambda_{n,A};t-x)$ is the reliability of the active 1-of-2 redundancy, which is formed by the pairs of functional units if the identical units in both sets are available.

(4) One functional unit on Set A fails at time x ($0<x<t$). Before time x, no unit on Set B fails in standby mode up to time x. This requires that the power supply on Set B survives in standby mode up to time x and is turned into active mode at