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Reliability evaluation of non-repairable phased-mission common bus systems with common cause failures

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ABSTRACT

Phased-mission common bus (PMCB) systems are systems with a common bus structure, performing missions with consecutive and non-overlapping phases of operations. PMCB systems are found throughout industry, e.g., power generating systems, parallel computing systems, transportation systems, and are sometimes characterized by their common cause failures. Reliability evaluation of PMCB systems plays an important role in system design, operation, and maintenance. However, current studies have focused on either phased-mission systems or common bus systems because of their complexity. The challenge in practice is to consider phased-mission systems together with common bus structures and common cause failures. To solve this problem, we propose an evaluation algorithm for PMCB systems with common cause failures by coupling the structure function of a common bus performance sharing system and an existing recursive algorithm. To weigh the efficiency of the proposed algorithm, its complexity is discussed. To improve the reliability of PMCB systems, we adopt the genetic algorithm method to search for the optimal allocation strategies of the service elements. We use both analytical and numerical examples to illustrate the application of the proposed algorithm.

1. Introduction

The phased-mission common bus (PMCB) system is a kind of phased-mission systems (PMS) consisting of service elements (SEs), nodes and a common bus. It performs a mission with consecutive and non-overlapping phases and aims at satisfying the demands of the nodes during each phase. The service elements in the system are allocated to the nodes and work to satisfy the demand of host nodes. The surplus performance of one node can be transmitted to a node with performance deficiency through the common bus, but the amount of redistributed performance during each phase cannot exceed the capacity of the common bus. The PMCB system fails if the demand of any node cannot be satisfied during a phase. Therefore, the reliability of a PMCB system can be defined as the probability that the demands of all the pre-specified nodes are satisfied during each phase. PMCB systems are found throughout industry, e.g., power generating systems, parallel computing systems, transportation systems, and are sometimes characterized by common cause failures (CCF). For example, consider a microgrid consisting of 4 diesel generators, 10 solar generators and 15 wind turbines. It distributes power through a common bus. The mission of power supply can be divided into two phases. During the day, the solar generators and the wind turbines can satisfy the load requirements in the microgrid, and at night, when the solar generators obviously cannot supply power the diesel generators and the wind turbines take over. All the solar generators may fail simultaneously because of extreme weather while the wind turbines can fail because of flutter. These common cause failures may result in significant economic losses. As the example suggests, the influence of common cause failures on the reliability of PMCB systems requires analysis.

Current reliability studies of the common bus system have two limitations. First, they are done separately from PMS studies because of their complexity. Second, they do not consider common cause failures. Despite these gaps, there is a certain amount of work on the topic. In one study, the common bus system can be used to share performance (Chang, 2014). The reliability of the MSS with performance sharing is first analyzed as a type of redundant system with two nodes (Lisnianski & Ding, 2009).

Abbreviations: SE, service element; PMS, phased-mission system; PMCB, phased-mission common bus; LCCS, linear consecutively-connected system; PM-LCCS, phased-mission LCCS; *r.v.*, random variable; GA, genetic algorithm; UGF, universal generating function; CDF, cumulative distribution function; CCF, common cause failures.

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Nomenclature

N	the number of nodes
M	the number of service elements
H	the number of phases in the phased-mission system
n_h	the number of nodes in phase h
D_h	the set of nodes in phase h
$d_h(j)$	the j -th nodes in the set D_h
$C_h(i)$	the demands of nodes i in phase h
$G_h(k)$	the performance of the service element k in phase h
$w(i)$	the set of SEs allocated to the node $i(1 \leqslant i \leqslant N)$
$X_h(k)$	the state of the binary service element k at the end of phase h
Y_h	the set of failed SEs at the end of phase h: $k \in Y_h$, if $X_h(k) = 0$; otherwise $k \notin Y_h$, if $X_h(k) = 1$
X_h	the state vector of service elements at the end of phase h
$S_{h,j}$	the cumulative performance of the service elements allocated to the nodes $d_h(j)$ in phase h
$C_{h,j}$	the demand of the nodes $d_h(j)$ in phase h
$E_{h,j}$	the surplus performance in the nodes $d_h(j)$
E_h	the total surplus performance in the system in phase h
$U_{h,j}$	the performance deficiency in the nodes $d_h(j)$
U_h	the total performance deficiency in the system in phase h
T_h	the limited capacity of the common bus in the system in phase h
$\tilde{T}_h$	the amount of the redistributed production performance in the system in phase h
$\tilde{U}_h$	the total performance deficiency after the common bus performance sharing in the system at the end of phase h
$\varphi_h(Y_h)$	the system condition at the end of phase h
$1(A)$	having the value 1 when A is true and the value 0 when A is false
$p_k(h)$	the conditional reliability of service element k $(1 \leqslant k \leqslant M)$ during phase h
$q_k(h)$	the conditional unreliability of service element k $(1 \leqslant k \leqslant M)$ during phase h
$F_k(t)$	the baseline distribution model for service element k $(1 \leqslant k \leqslant M)$
$F_{ki}(h,t)$	the stress dependent failure distribution for service element k $(1 \leqslant k \leqslant M)$
$\Phi_{ki}(h)$	the cumulative failure probability for service element k $(1 \leqslant k \leqslant M)$
$\alpha_i(h)$	the acceleration factor
τ_h	the duration of the phase
f_{ki}	the failure probability during a phase
$\varepsilon_i(h)$	the probabilities of CCF for the node $i(1 \leqslant i \leqslant N)$ in phase h
$\theta = \{e_1, e_2, \ldots, e_m\}$	a set of m SEs
$\theta_r = g(\theta, r)$	a possible subset θ_r of the set θ
$g(\theta, r)$	a function of the set θ and integer value r, return the r -th subset θ_r
x	maximal integer number that does not exceed x
$mod_2 x$	function of integer argument x that returns 1 when x is odd, 0 if x is even;
$B = \{b_1, \ldots, b_s\}$	a realization of the random set Y_h
$B_r = g(B, r)$	the numbers of failed SEs during phase h
$B - B_r$	the numbers of failed SEs at the beginning of the current phase
$v(i) = w(i) \cap B_r$	intersection between the allocation $w(i)$ and the failed SEs B_r
$A = \{1, 2, \ldots, M\}$	set of M SEs
$Q_h(B, r)$	the conditional probability of the system states
$Z_{h,B}$	the probability of the random set Y_h whose realization is B

The performance in the redundant system can be only transmitted from the assisted node to the main node in a single direction. In another study, the reliability of a multi-state system (MSS) with common bus performance sharing can be evaluated based on the universal generating function method (Levitin, 2011). The nodes in the MSS are all connected directly to the common bus. The surplus performance in each node can be transmitted to any other node through the common bus. The MSS can handle a static common bus system without PMS and is widely used in industrial systems, such as manufacturing (Chalabi, Dahane, Beldjilali, & Neki, 2016; Lin & Chang, 2012; Lin, Huang, & Huang, 2016). An investigation of the instantaneous availability of a repairable MSS with a common bus system using Lz-transform methods (Yu, Yang & Mo, 2014) finds the failures of components are independent. In a study of series-parallel MSS systems with common bus performance sharing (Xiao & Peng, 2014), the optimal allocation strategies and maintenance strategies are solved to minimize the total maintenance cost with the constraints of pre-specified system availability; the failures of the components are also independent. The effect of protecting from external impacts, such as natural disasters or terrorism, is considered in a study of the MSS with common bus performance sharing (Xiao, Shi, Ding, & Peng, 2016); the system's components have constant failure rate during the entire system lifetime, and the failures are independent. The optimal defense and attack strategies for a system with common bus performance sharing are studied in Zhai, Ye, Peng, and Wang (2017); its components may fail because of both internal causes and intentional attack, except for common cause failures. The MSS with common bus performance sharing is extended to the MSS with two performance sharing groups by Peng, Liu, and Xie (2016); the proposed system has two common bus structures without PMS. The limited size of a performance sharing group is taken into account in a series system in Peng, Xiao, and Liu, (2017). Finally, the parameters of the component lifetime distribution of the components in a k-out-of-n load-sharing system are estimated using the failure data of the system without CCF (Kong & Ye, 2016). Overall, however, neither the PMS nor the CCF has been considered in reliability studies of the common bus system.

The main structures of the PMS are series-parallel systems, k-out-of-n systems and linear consecutively-connected systems (Levitin, Xing, & Dai, 2013; Levitin, Xing, & Yu, 2014). Relevant evaluations of PMS reliability include the following. The reliability of the PMS with multiple failure mode components can be evaluated using the binary decision diagram (BDD) and fault tree (FT) method Reed, Andrews, & Dunnett, 2011. Meanwhile, the optimal component testing problem is solved by the cutting plane method and column generation technique (Feyzioğlu, Altınel, & Özekici, 2008). The reliability of the PMS for series-parallel systems and k-out-of-n systems can be analyzed using the multiple-valued decision diagram (MDD) and FT Mo, Xing, & Amari, 2014. The reliability and optimal structure of series-parallel PMS subject to fault-level coverage are determined using the universal generating function (UGF) (Peng, Zhai, Xing, & Yang, 2016). The reliability of the phased-mission LCCS (PM-LCCS) and the PMS with series-parallel systems can be evaluated by the recursive algorithm (Levitin, Xing, & Amari, 2012; Levitin, Xing, Amari, & Dai, 2013). The recursive algorithm can be applied to the PMS without FT. The reliability of the PMS can be estimated with stochastic filtering