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Heterogeneous redundancy optimization for multi-state series–parallel systems subject to common cause failures

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ABSTRACT

Components will fail when loads (such as humidity, temperature, vibration, shock) are beyond the limits, which is a kind of common cause failures. In order to provide a desired level of reliability with minimum cost, the optimal model of multi-state series–parallel system subject to this kind of common cause failures is formulated. The universal generating function is adapted to analyze the reliability of multi-state system with mixing of components of different types, and genetic algorithm is used to solve the optimal model. A numerical example is illustrated to demonstrate the proposed method. The results show that common cause failures make the redundancy allocation strategy different. To provide the desired level of reliability with minimum cost, the mixture of components of different types is a very effective method.

1. Introduction

Components redundancy is an effective method to provide the required level of reliability. But the effect of redundant components is reduced because of common cause failures (CCFs). CCF exists in many systems composed of redundant components, and makes the systems unreliable. CCF is the simultaneous failure of multiple components due to a common cause (CC). The origin of CC events includes environmental loads (humidity, temperature, vibration, shock, etc.), errors in maintenance and system design flaws. The subject of CCF has attracted considerable attention, and many papers have focused on reliability analysis of systems subject to CCF [1–6] and CCF rates estimation [7–10].

The current research achievements are mainly applied to solve CCF problems of binary systems which only have two states: perfect functioning or complete failure. Many systems are actually multi-state systems (MSSs), and they can work in different performance levels from perfect functioning to complete failure [11,12]. Reliability analysis of MSS subject to CCF is rather different from that of binary systems. Levitin adapted the universal generating function (UGF) method to incorporate CCF into non-repairable MSS, and presented a straightforward procedure to evaluate reliability functions of non-repairable MSS with CCF [13]. The MSS in [13] is composed of binary components, and the proposed procedure can only be used in this situation. When MSSs consisting of multi-state components use substantial component redundancy and diversification to provide high levels of system reliability [14], new method must be proposed for system reliability estimation. Then the problem is that when the MSS subject to CCF consists of multi-state and non-identical components, how to analyze the system reliability and optimize the system structure.

If all the possible failures caused by CCF are taken into account, it is very difficult and may be not necessary. Levitin [15] considered a special case named common supply failures in linear multi-state sliding window systems. The common supply failure affects mutually exclusive sets of components, and all the components belonging to the same common supply group fail as a result of common supply failure. Another special case will be analyzed in this paper. Sometimes MSS may suffer from severe environmental loads (such as humidity, temperature, vibration, shock) when they are working. When these loads are beyond the limits of components, the components will fail. For example, in the first quarter of 2008, the southern provinces of China suffered from the worst snow disaster in more than 5 decades in most areas and the longest lasting blizzard in 100 years. 30–60 mm of ice forming on power lines which were designed to withstand about 10–15 mm of ice pulled down a lot of transformer substations. This led to cut-offs in the supply of electricity, and resulted in direct economic loss of 6 billion dollars. Faced with severe environmental loads, greater challenges are imposed on the safety of MSSs.

In this paper, the reliability of multi-state series–parallel system subject to CCF caused by severe environmental loads is

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Nomenclature

Acronyms

CC	common cause
CCF	common cause failure
MSS	multi-state system
UGF	universal generating function
GA	genetic algorithm

Notation

N	number of subsystems in the system
h_i	total number of different types of components used in subsystem i
H_i	total number of different types of components available for subsystem i
t_{ij}	representation of components type j in subsystem i in Fig. 1
$k_1, \cdots, k_{h_i}$	version number of components used in subsystem i
$\mathbf{g}_{ij}$	performance set of components type j in subsystem i
$\mathbf{q}_{ij}$	probability set of components type j in subsystem i
c_{ij}	cost of components type j in subsystem i
n_{ij}	number of components type j used in subsystem i
n_i	total number of components used in subsystem i
$n_{\max}$	maximum number of components allowed in each subsystem
C	cost of the system
f	the subsystem subject to CCFs
w	required performance level of the system
$R(w)$	system reliability when the required performance level is w
R_0	the specified minimum required level of system reliability
Z^+	the space discrete of positive integers
Z	the space discrete of integers
M	number of possible states of components
M_i	number of possible states of subsystem i
M_{sys}	number of possible states of the system
$U_{ij}(z)$	UGF of components type j in subsystem i
$U_i(z)$	UGF of subsystem i
$U(z)$	UGF of the system
$\mathbf{v}_k$	representation of chromosome
f_k	individual fitness
p_c	crossover probability
p_m	mutation probability

studied, and the heterogeneous redundancy allocation problem is solved. Components in the same subsystem can be different, and both components and the system are multi-state. The UGF is used to estimate the system reliability, and the genetic algorithm (GA) is used to optimize the system structure. The result of redundancy allocation problem considering CCFs is compared with the result without CCFs.

The structure of this paper is organized as follows. The problem is formulated in Section 2. The reliability of MSS is estimated in Section 3. GA is proposed for solving the redundancy problem in Section 4. A numerical example is illustrated to demonstrate the proposed method in Section 5. Finally, conclusions are given in Section 6.

2. Problem formulation

General assumptions:

(1) The components are not repaired.
(2) The system and components are multi-state.
(3) Mixing of components of different types in the same subsystem is allowed.
(4) When any load is beyond the limit of components, all components of this type will fail.

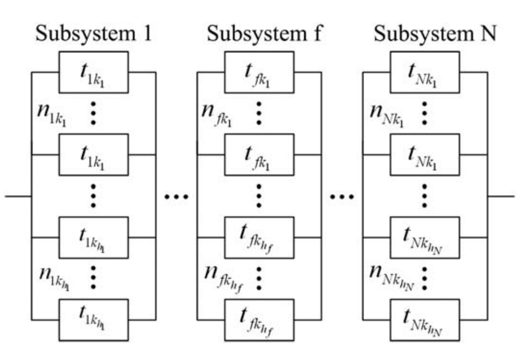

Fig. 1. Structure of a multi-state series–parallel system.

2.1. A multi-state series–parallel system with CCFs

A multi-state series–parallel system is composed of N subsystems connected in series, and subsystem i consists of h_i different types of components in parallel, as depicted in Fig. 1. There are H_i different types of components that can be selected for subsystem i in the market. The components are multi-state and sorted by performance $\mathbf{g}_{ij}$, reliability $\mathbf{q}_{ij}$ and cost c_{ij}. There are total n_i components used in subsystem i. The cost of the system is C, and the reliability of the system is $R(w)$ when the required performance level is w. To analyze the effect of CCFs on the system reliability, assume that subsystem f is subject to CCFs.

2.2. Mathematics model

The objective is to minimize the cost of the system subject to the specified minimum required level of system reliability. The redundancy allocation problem of this system can be formulated as

$$\text{Min} \quad C = \sum_{i=1}^{N} \sum_{j=1}^{H_i} n_{ij} c_{ij} \tag{1}$$

$$\text{s.t.} \quad R(w) \geq R_0 \tag{2}$$

$$1 \leq n_i \leq n_{\max} \tag{3}$$

$$n_{ij} \in Z, n_{ij} \geq 0 \tag{4}$$

$$n_i, n_{\max} \in Z^+ \tag{5}$$

j is the version number of components available for subsystem i, $i=1,2,\ldots,N$, $j=1,2,\ldots,H_i$, $\sum_{j=1}^{H_i} n_{ij} = n_i$.

3. Reliability estimation of the system

Generally speaking, the methods of MSS reliability estimation are based on four different approaches: the UGF technique, the structure function approach, the stochastic process approach and the Monte Carlo simulation technique [12]. In these four methods, the UGF method is proven to be very effective for high-dimension