Evaluation of the Reliability of a Standby Redundancy System Under Real Conditions

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Abstract

This paper presents a novel analysis of a standby redundancy system under real conditions. The study considers the presence of a real commutator and failure detector in the system. Through a comprehensive failure mode analysis, mathematical relationships between different module characteristics are established. The results of investigation provide valuable insights for manufacturers, allowing them to evaluate the Mean Time To Failure (MTTF) of the system during the design phase and make informed decisions regarding the selection of failure rates for the detector and commutator. Overall, this work contributes to the effective operation of standby redundancy systems in practical applications.

Notations

SR	:	Standby Redundancy
PD	:	Principal device
SD	:	Standby device
MTTF	:	Mean Time To Failure
T	:	Mean Time To Failure of PD and SD
$R(t)$	:	Survivor function of PD and SD
$f(t)$	:	Failure density function of PD and SD
$F(t)$	:	Failure distribution function of PD and SD
λ	:	Failure rate of PD and SD
DF	:	Detector of Failure
$F_d(t)$	:	Failure distribution function of detector
λ_d	:	Failure rate of detector
R_c	:	Reliability of commutator
λ_c	:	Failure rate of commutator
$\cap$	:	Symbol of events intersection
$\overline{C}$	:	Logical complement of C
SRC	:	Synthetic Reliability of Commutator

1 Introduction

Reliability is a fundamental concept in engineering and refers to the ability of a system, product, or component to perform its intended function without failure over a specified period of time and under specified conditions. It is a critical factor in ensuring the dependability and trustworthiness of various systems, ranging from everyday consumer products to complex industrial systems. Reliability is essential because failures can lead to various undesirable consequences, including financial losses, damage to reputation, safety hazards, and disruptions to operations. Therefore, engineers and designers strive to develop reliable systems that meet the required performance standards and maintain their functionality over their intended lifespan [1–3].

Reliability consideration is very much a part of the design stage of a system. However, it is beneficial to first consider the main ways that the reliability of a system can be modified. There are two main ways in which reliability can be affected. The first relates to quality, and the second to redundancy [4–7].

Redundancy involves incorporating duplicate components or systems within a larger system to provide backup or alternative pathways in case of failure. Redundancy can improve system reliability by reducing the

likelihood and impact of failures. Redundancy is of two types: active and standby [8–10].

Active redundancy involves the simultaneous operation of redundant components or systems, where they share the load and provide immediate backup in case of failure. Active redundancy can help maintain system functionality without interruption [10–14].

Standby redundancy, also known as cold redundancy, involves detection mechanisms and switching, redundant components or systems that are on standby and activated only when the primary component or system fails [15–18].

The detection mechanism in the standby redundancy is responsible for monitoring the operational status of the primary component and identifying when it fails. It can employ various techniques, such as sensors, monitoring circuits, or feedback signals. However, the detection mechanism may not always provide immediate or foolproof detection, and there can be instances of false positives or false negatives [19–21].

The switching mechanism in the standby redundancy is responsible for activating the redundant component upon detection of a failure in the primary component. It can involve mechanical, electrical, or software-based switching mechanism. The switching process may introduce a certain delay or transient period during the switchover, which can impact the system's reliability [8, 9].

In standby redundancy, detection of the failed component and activation of the redundant one are both performed by a detection and switching mechanism not necessarily perfect. However, these mechanisms may not be perfect and can introduce some degree of uncertainty or delay in detecting and switching to the redundant component. This can impact the overall reliability of the standby redundancy system [9, 22, 23].

The reliability of the detection and switching mechanism is a critical aspect of standby redundancy systems. The probability of correctly detecting a failure and switching to the redundant component when needed is a key factor in determining the overall reliability of the system. This reliability can be influenced by factors such as the design and quality of the detection and switching mechanisms, the effectiveness of monitoring and feedback systems, and the response time of the switching process [20, 24].

Lots of work has been done by many researchers in the area of reliability, and in particular, standby redundancy. Sharifi and Pedram [7] derived the formula to calculate the reliability of the system with an active redundancy strategy using the Markov process when the components' life have a Weibull

distribution. Jasdev B. and Mohit K. [5] have analyzed the active standby redundancy when initially both similar units are observed to be in an operative situation. Chao G. and Xing M. [8] have studied the stability of a standby system with an unreliable server and switching failure, where both the time-to-repair of units and the time-to-repair of the server follow general distributions. Dong Y. Chia H. [9] has involved the evaluation of the availability and reliability of a repairable system containing warm standby components and undergoing switching failure. Linmin H. and Zhuoxin B. [17] have studied active redundancy under the assumption that the switch is completely reliable. Kuo H. and Chia H. [20] have analyzed the case when the primary and standby virtual machines are both assumed to be unreliable with warm standbys and switching failure. Ying L. and Jau Ch. [25] have analyzed the characteristics of a redundant repairable system when switching to standby fails, and times to failure and times to repair of the operating units are assumed to follow exponential distributions.

Most of the above-mentioned studies and also [9, 10, 19, 23, 25] are all about the reliability of standby redundancy systems. They are based on purely theoretical considerations; they assume the case where the switch and failure detector are ideal [24, 26–29]. In reality, these two devices can fail either in the standby phase or during the switching phase.

On the other hand, the assumption of a constant failure rate (exponential distribution) implies that the failure probability remains constant over time and is not dependent on the time since the last failure. This simplifies the calculations of reliability and availability for the active redundancy system, as the exponential distribution has well-defined mathematical properties [5, 8, 15]. This article focuses on standby redundancy in real-world conditions where the commutator and detector of failure are both not perfect but are characterized by a constant failure rate during their operation. The present paper focuses on the problem of redundancy in the real case, where the fault detector and the switch are considered not perfect but real, characterized by a known failure rate.

2 Active Redundancy System

In general, a standby redundancy system is composed of a primary device (PD), a standby device (SD), a commutator (C), and a failure detector, as shown in Figure 1.

The primary device (PD) and the standby device (SD) are characterized, respectively, by a constant failure rate λ. The commutator is characterized by
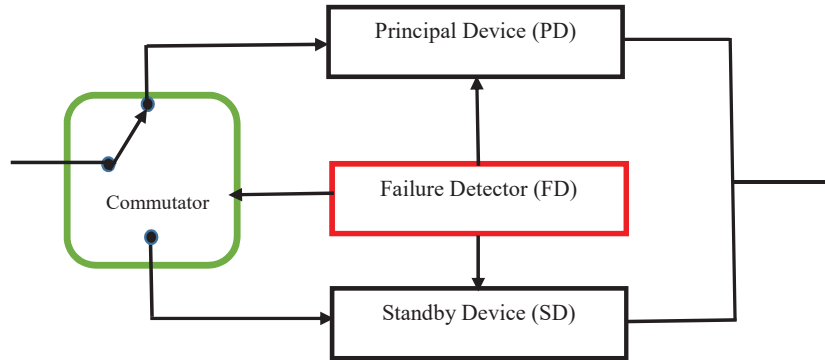
Figure 1   Structure of standby redundancy system.
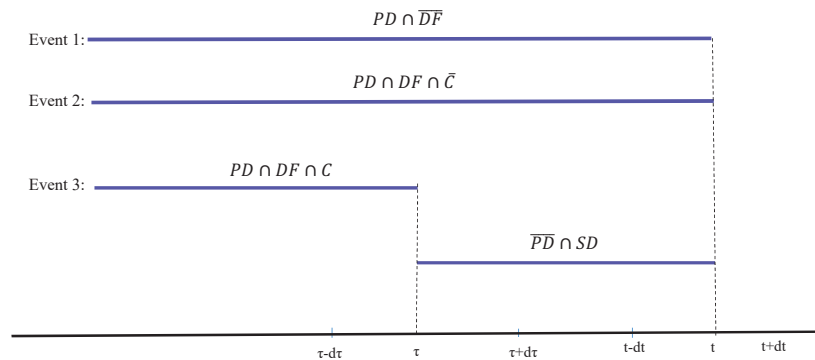
Figure 2   Failure modes of the considering system.

a constant switching probability Rc throughout the entire operating period, while the failure detector is characterized by a constant failure rate λ_d.

3 Mathematical Analysis of Failure Modes

The analysis of failure modes in this system leads us to distinguish the following three events, as indicated in Figure 2, where:

– symbol denotes the intersection of events and
– symbol represents the logical complement of event X.

Event 1

- The principal device fails within the time interval $(t, t + dt)$,
- The failure detector fails to detect the failure of the principal device.

Therefore, the probability of this event is:

$$f_p(t)F_d(t) \tag{1}$$

Event 2

- The principal device has failed within the time interval *dt*,
- The failure detector detects the failure.
- However, the commutator is not working.

In this case, the probability of this event is:

$$f_p(t)R_d(t)F_c \tag{2}$$

Event 3

- The principal device has failed within the time interval $(\tau, \tau + d\,\tau)$ with $\tau < t$.
- The failure detector detects the failure.
- The commutator is working.
- However, the standby device is not operational, having failed during the standby phase.

In this case, the probability of this event is:

$$f_p(\tau)R_d(\tau)R_cf_s(t - \tau) \tag{3}$$

Since the three previous events are independent of each other, the failure density function of the standby redundancy system is given by:

$$f_{SR}(t) = f_p(t)F_d(t) + f_p(t)R_d(t)F_c + \int_0^t R_cf_p(\tau)R_d(\tau)f_s(t - \tau)d\tau \tag{4}$$

Let's assume now that the failures of the primary device and the auxiliary device follow the exponential distribution with a constant failure rate λ.

$$F_p(t) = 1 - e^{-\lambda t} \tag{5}$$

and the failure density function of PD and SD are:

$$f_p(t) = f_a(t) = \frac{dF_p(t)}{dt} = \lambda e^{-\lambda t} \tag{6}$$

where λ is the constant failure rate for both components (PD and SD).

Let's also assume that the failure distribution function of the failure detector, denoted as $F_d(t)$, also follows the exponential distribution with a constant failure rate λ_d. In this case, the failure distribution function for the failure detector can be expressed as:

$$F_d(t) = 1 - e^{\lambda_d t} \tag{7}$$

where λ_d is the failure rate of the failure detector.

Considering also that the switch is characterized by a constant switching probability R_c. In this case, the failure density function of the considered system can be expressed as follows:

$$f_{SR}(t) = \lambda e^{-\lambda t} \left(1 + R_c \frac{\lambda}{\lambda_d} - R_c \left(1 + \frac{\lambda}{\lambda_d}\right) e^{-\lambda_d t}\right) \tag{8}$$

After integration expression (8) and simplification, the reliability function of this system can be expressed by the following Equation (9).

$$R_{SR}(t) = \int_t^\infty f_{SR}(t) dt = \left(1 + \frac{\lambda}{\lambda_d} R_c\right) e^{-\lambda t} - R_c \left(\frac{\lambda}{\lambda_d}\right) e^{-\lambda_d t \left(1 + \frac{\lambda}{\lambda_d}\right)} \tag{9}$$

This last relationship is extremely important from a practical point of view, especially when it comes to evaluating the level of the reliability during the design phase of a strategic system where the consequences of a failure can be catastrophic. The role of the manufacturer and designer of such a system is to set a maximum margin for the failure rate, particularly for the failure detector, to ensure that the considered system meets the required reliability requirements.

Generally, these requirements are expressed in two forms:

– Either in terms of the mean time to failure MTTF or,
– In terms of the probability of functioning properly until a specific time t.

4 Reliability Requirement Assurance in Terms of MTTF

In this paper, our focus is limited to the case where the reliability requirement assurance is expressed specifically in terms of MTTF. Equation (7) provides the expression for the mean time to failure of the active redundancy system TAR.

$$T_{SR} = \int_0^\infty R_{SR}(t) dt \tag{10}$$
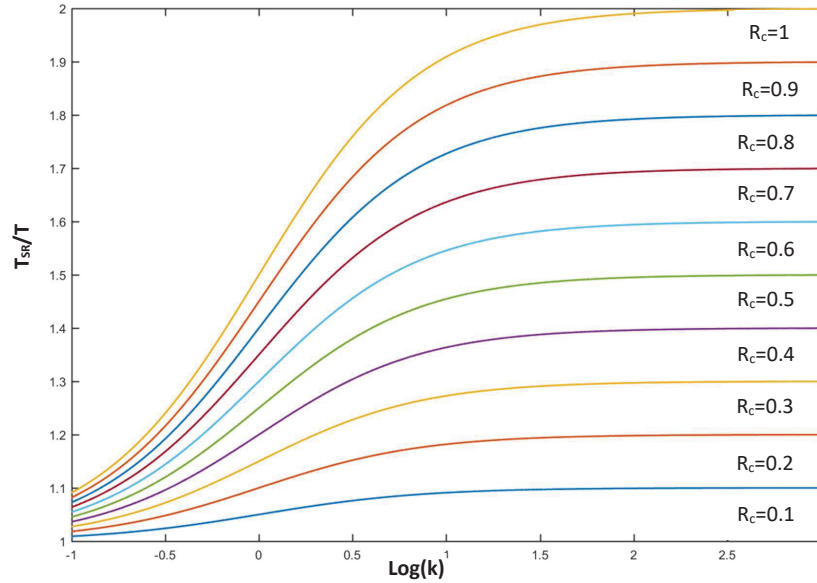
Figure 3 Normalized average time characteristics T_{SR}/T as a function of $k = \log\left(\frac{\lambda}{\lambda_d}\right)$ with R_c as a parameter.

Which can be formulated using Equation (9) and after integration and simplification, by the following relation:

$$T_{SR} = T\left(1 + R_c\left(\frac{k}{k+1}\right)\right) \qquad (11)$$

Where $T = 1/\lambda$ represents the MTTF of the primary device, and $k = \frac{\lambda}{\lambda_d}$.

The normalized mean time T_{SR}/T of the standby redundancy system, as a function of the ratio of the failure rate of the primary device λ to the failure rate of the failure detector λ_d, with the commutator reliability R_c as a parameter, is presented in Figure 3.

The normalized mean time T_{SR}/T of the standby redundancy system, as a function of the ratio of the failure rate of the primary device λ to the failure rate of the failure detector λ_d, with the commutator reliability R_c as a parameter, is presented in Figure 3.

The family of curves in Figure 3 is characterized by the existence of a certain level beyond which the reduction in the failure rate of the detector compared to the failure rate of the principal device has no significant influence on improving the mean time to failure of the standby redundancy

system. In other words, for a given level of R_c, the detector of failure is considered ideal when its failure rate λ_d is approximately 100 times smaller than the failure rate of the primary device λ.

5 Synthetic Reliability of Commutator (SRC)

In practice, the reliability of the commutator R_c is often not constant but decreases over time during system operation. According to the principle of on-demand operation of the commutator, the random variable t, which determines the life time of PD, also represents the waiting time for operation, as at time t, PD will be switched Off and SD will be switched ON with a probability equal to:

$$R_c(t) = e^{-\lambda_c t} \tag{12}$$

Where λ_c represents the failure rate of commutator.

This paper presents a novel indicator called Synthetic Reliability of Commutator (SRC), represented as $\overline{R_c}$. It is defined as the average probability of correct operation of the commutator on demand over all possible operating times until the failure of PD:

$$\overline{R_c} = \int_0^\infty R_c(t) f_p(t) dt \tag{13}$$

By substituting Equations (6) and (12) into expression (13) and integrating, we obtain:

$$\overline{R_c} = \frac{1}{1 + \frac{\lambda_c}{\lambda}} \tag{14}$$

The derived expression $\overline{R_c}$, presented as a function of the ratio of the commutator failure rate λ_c to the failure rate of the standby device λ, has an interesting physical interpretation.
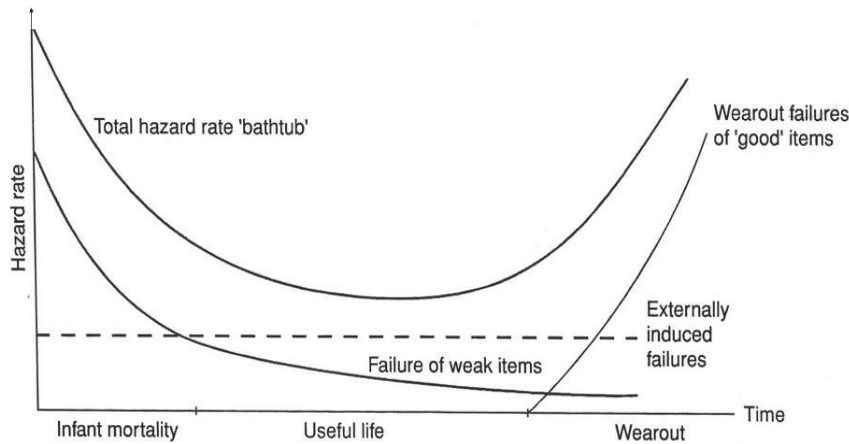
Since

$$\lim_{\frac{\lambda_c}{\lambda} \to \infty} \overline{R_c} \to 1 \tag{15}$$

So, a real commutator approaches ideal behavior when:

– The failure rate of the commutator is equal to zero, $\lambda_c = 0$ (i)
– The failure rate of the commutator λ_c is relatively small compared to the failure rate of the standby device $\lambda_c \ll \lambda$ (ii).

The condition (i), mentioned in [1–3], is commonly considered as the criterion for an ideal commutator.

Figure 4   Normalized Bathtub curve-typical shape of the failure rate.

On the other side, the condition (ii) holds special significance in practice, as it indicates that the ideality of a commutator is a relative concept and is dependent on the mutual relationship between the commutator failure rate λ_c and the failure rate of the standby device λ.

By transforming the relationship (14), we obtain the failure rate of the commutator:

$$\lambda_c = \lambda \left(\frac{1 - \overline{R}_c}{\overline{R}_c} \right) \tag{16}$$

So far, the exact relationship between λ_c and λ is not fully determined, as indicated by Equation (16), where the ratio $\frac{\lambda_c}{\lambda}$ is dependent on the reliability of the commutator R_c. On the other side, R_c cannot take any arbitrary value but is determined based on specific reliability requirements.

6 Standby Redundancy in General Case

In fact, the general shape of the failure rate function of any technical device follows a bathtub curve, which can be primarily divided into three different intervals:

 – Infant mortality interval corresponds to failure of "week" items,
 – Useful life interval corresponds to externally induced failures and
 – Wear-out interval corresponds to wear out failures of "good" items.

The period where the failure rate starts to increase, known as the wear-out period. Users of such systems can mitigate the increase in failure rate through

systematic controls and the implementation of regular preventive maintenance policies. By doing so, they can prolong the useful life of the system and maintain a relatively constant failure rate.

The period of infant mortality, characterized by a decreasing hazard rate. In most cases, this decrease is rapid and stabilizes to a relatively constant failure rate. This is often observed in electronic components and systems. Manufacturers of electronic systems typically eliminate this rapid decrease in failure rate by subjecting the components to rigorous testing involving extreme conditions of temperature, pressure, humidity, and vibrations. This process helps eliminate weak components from the market, resulting in products that exhibit a relatively constant failure rate over a long period of operation.

On the other hand, obtaining reliability characteristics for standby redundancy systems presents analytical challenges (look at Equations: (4), (9), (10), (13)), especially when the constituent components have failure rates that deviate from the exponential model and instead follow the Weibull distribution with a shape parameter "b".

$$\mathrm{R(t)} = e^{-\left(\frac{t}{a}\right)^b} \tag{17}$$

A value of (b < 1) corresponds to a decreasing failure rate, while a value of (b > 1) corresponds to an increasing failure rate, (b = 1) corresponds to a constant failure rate.

At this stage, we can consider the primary Principal device and the standby device as obeying the Weibull distribution, while the switch and failure detector follow the exponential distribution. If this is not the case, analytical resolution of the standby redundancy problem becomes infeasible. In such situations, statistical simulation methods like Monte Carlo simulation can be employed.

7 Conclusions and Future Work

This article presents a comprehensive investigation into the implications of non-ideal components within standby redundancy systems. The study focuses on the challenges encountered during the standby and switching phases, including switching delays, transient periods, switching errors, false alarms, and missed failures.

In terms of reliability requirements expressed as the mean time to failure, the research findings highlight the significance of parameter selection for the

failure detector and commutator in achieving optimal system performance. Specifically, it is observed that a failure detector with a substantially lower failure rate (λ_d) compared to the primary device failure rate (λ) is essential. Empirically, a ratio of λ/λ_d that is at least 100 times smaller is recommended to attain an ideal active redundancy system.

Furthermore, the concept of Synthetic Reliability of the Commutator is introduced as a metric for evaluating the performance of real commutators. The analysis reveals that a commutator can be considered to operate with near-perfection when the ratio of the commutator failure rate (λ_c) to the principal device failure rate (λ) is significantly smaller than 1.

Overall, these research findings contribute to a deeper understanding of the implications of non-ideal components in standby redundancy systems. The insights gained from this study provide valuable guidelines for parameter selection and introduce a novel metric to assess the performance of commutators in real-world scenarios.

As a future work in this paper, we can consider studying the general case where the failure of the switch, failure detector, as well the primary and auxiliary devices, is not constant but follows the Weibull model $R(t) = e^{-\left(\frac{t}{a}\right)^b}$. This model, with its shape parameter "b" allows distinguishing between the infant mortality period (b < 1) and the wear-out period (b > 1). This approach can be considered very close to reality and can be the subject of extending this paper to the general case where the failure rate of all active redundancy devices is no longer constant but variable over time.

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