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COMMON CAUSE FAILURE PROBABILITY ANALYSIS METHOD AND ITS APPLICATION TO MORE ELECTRIC AIRCRAFT ELECTRICAL POWER SYSTEMS

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Abstract

The more electric aircraft (MEA) electrical power system is designed with multiple types of redundancy to improve safety, consequently more attentions need to be paid to common cause failure. Considering common cause failure types of redundant systems, the comprehensive probability correction model based on multiple algorithms is proposed. The different common cause failure algorithms, such as β, α, and the square root model are analysed for similar redundancy and non-similar redundancy systems with or without operational data, and the process for solving the common cause failure probability of system synthesis is investigated. Further research is carried out on the application of failure probability correction for aviation batteries and transformer rectifier units (TRU) of MEA. The results show that the proposed comprehensive probability correction model is effective, and can be applied to airborne complex systems. The research complements the safety assessment theory, and lays a foundation for the common cause failure probability correction and safety design of systems.

Key Words

Common cause failure, electrical power system, β-factor, α-factor

Notations

$\alpha_k^{(m)}$	The k -components common cause failure factor
C	The combination of different TRU common cause failure
$P(A_F)$	The failure probabilities of A
Q_{CC}	The common cause failure probability
$Q_k^{(m)}$	The failure probability of the particular k-components
Q_{SS}	The failure probability of the redundant system
$\lambda_{ordinary}$	Failure rate of the ordinary TRU
β	The ratio of common cause failure to total failure
F	Failure probability
$P(B_F)$	The failure probabilities of B
Q_I	The component independent failure probability
$Q_K^{(m)}$	The failure probability of any k-components
λ_{new}	Failure rate of the new TRU

1. Introduction

The redundancy design can significantly improve the safety of the system [1] and has been used many times in the more electric aircraft (MEA) electrical power system [2]. Based on whether the components are identical, redundant systems can be divided into similar redundancy and non-similar redundancy. The two identical batteries for emergency power supply and two starter-generators for starting of each engine or auxiliary power unit are typical similar redundancy [3]. Multiple AC/DC buses for hybrid power supply and the simultaneous use of hydraulic and electric actuators are typical non-similar redundancy [4]. Affected by internal and external environment, installation, maintenance and other factors, there are two or more components failed simultaneously in multi-redundant system, which is called common cause failure [5]. Due to

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the serious consequence of common cause failure, and the redundant components cannot be considered as completely independent of each other, the failure probability of redundant system need to be corrected.

Scholars at home and abroad have proposed different construction methods of common cause failures probability models and the reliability calculation methods for redundant systems. Singh and Singh [6] taken the triple redundant nuclear power plant system as an example and proposed the construction method of basic probability models for different failure quantities by screening analysis and detailed analysis. Cao *et al.* [7] proposed a reliability allocation method for system components considering common cause failures and verify the method by studying series and parallel redundant systems. Zeng and Sun [8] taken the competing failures of redundant components as the research object and proposed a modelling approach and reliability calculation method of common cause failure. Mathebula and Saha [9] analysed the architecture of the two-redundant protection system for synchronous motors, construct the Markov model considering common cause failure, and analysed the effect of different fault diagnosis rates and different common cause failure probabilities on system safety. Wang and Xing [10] proposed a multi-stage task reliability model considering common cause failures using multi-valued decision diagrams, and proved the validity of the method in terms of both reliability results and the sequence of events. Cannon *et al.* [11] investigated the relationship between reliability and common cause failure rate and maintenance rate of triple redundant system using Markov model. Oliva *et al.* [12] constructed a redundant system unavailability model from the perspective of system aging and performance degradation to realise system common cause failure assessment. Bao *et al.* [13] proposed the PRADIC framework to support risk assessment, reliability analysis and consequence protection of multi-redundancy systems, analyse the common cause fault tree construction and failure probability analysis method, and verify the effectiveness of the method by taking the digital instrumentation and control system of nuclear power plant as an example. Meanwhile, based on the operation and maintenance data Fleming and others have proposed β-factor model [14], α-factor model [15], and multi-Greek letter model [16] for the quantitative analysis of common cause failure for di-redundancy, tri-redundancy, and multi-redundancy. Further researches combining D-S evidence theory [17] and Bayesian networks [18] have also been reported to construct uncertainty models for common cause failure.

The existing researches on common cause failure probability models mainly focus on the theoretical analysis, but pay few attentions to practical application and method validation. What's more, the development and safety analysis of MEA electrical power system in China is still in the beginning stage. Meanwhile, the effectiveness of the application of common cause failure method in aviation needs to be analysed, which is originated and widely used in nuclear engineering. The analysis of common cause failures will provide guidance for the safety analysis and design optimisation of the electrical power system. What's more,

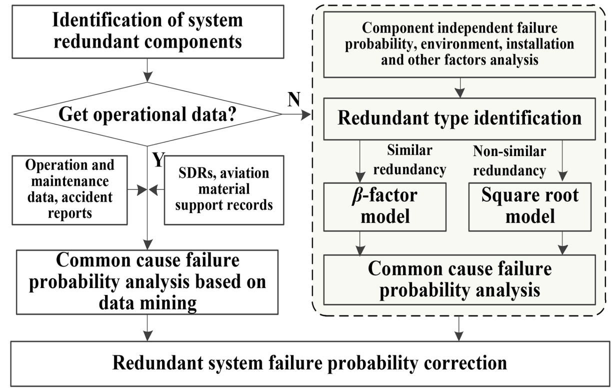

Figure 1. System failure probability correction.

there is nearly no previous research on considering the probability correction of common cause failure, and the correcting the failure probability for aircraft system.

In this paper, we propose a comprehensive probability correction model for electrical power system and provide a more accurate calculation of the system failure probability, which considering the common cause failure. In addition, the probability correction model application on the MEA electrical power system is analysed. The remainder of this paper is organised as follows. The methods of constructing correction models of common cause failure probability for different types of redundant systems are introduced in Section 2. The application of common cause failure probability analysis method in MEA electrical power system is analysed in Section 3. Finally Section 4 summarises the contents and gives a prospect.

2. Comprehensive Failure Probability Correction Method Considering Common Cause Failure

Constructing common cause failure probability model is essential for redundant system safety evaluation and probability correction. The comprehensive probability correction model for various types of redundant system is proposed and is shown as Fig. 1.

2.1 Common Cause Failure Probability Analysis With Operational Data

Common cause failure is the simultaneous failure of two or more components in a very short period of time. Component failure sequence and maintenance records are related in time. After obtaining the operation and maintenance data of the system, accident report, service difficulty report (SDR), aviation material support record, and other operation data, the failure correlation data can be analysed and obtained by data mining method, and the common cause failure probability is further solved. The common cause failure probability analysis method based on data mining is suitable for similar redundancy and non-similar redundancy.

Taking the operational data as an example, the failure probability of all redundant components and the simultaneous failure probability of multiple redundant components are obtained by data mining, and the common cause failure coefficients of different number of components can be analysed by combining the α-factor model [19]. For a redundant system of m components, assume that the failure probability of the particular k components is $Q_k^{(m)}$, the failure probability of any k components $Q_K^{(m)}$is:

$$Q_K^{(m)} = \frac{m!}{(m-k)!k!} Q_k^{(m)} \tag{1}$$

The failure probability of the redundant system Q_{SS} is:

$$Q_{\mathrm{SS}} = \sum_{J=1}^{m} Q_J^{(m)} = \sum_{j=1}^{m} \frac{m!}{(m-j)!j!} Q_j^{(m)} \tag{2}$$

Define $\alpha_k^{(m)}$ as the k -components common cause failure factor:

$$\alpha_k^{(m)} = \frac{Q_K^{(m)}}{Q_{\mathrm{SS}}} = \frac{\frac{m!}{(m-k)!k!} Q_k^{(m)}}{\sum_{j=1}^{m} \frac{m!}{(m-j)!j!} Q_j^{(m)}} \tag{3}$$

After obtaining the common cause failure coefficients of different number of components, not only can the common cause failure probability and the comprehensive failure probability of redundant system evaluated in the design stage be corrected but also can provide guidance for system safety optimisation.

2.2 Common Cause Failure Probability Analysis Without Operational Data

When there is a lack of operational data during the design phase or early operation, the β-factor model can be used to estimate the similar redundancy common cause failure probability, and the square root model can be used to estimate the non-similar redundancy common cause failure probability.

2.2.1 Similar Redundant System

Assuming that Q_I is the component independent failure probability, Q_{SS} is the redundant system failure probability, and Q_{CC} is the common cause failure probability, define β as the ratio of common cause failure to total failure:

$$\beta = \frac{Q_{\mathrm{CC}}}{Q_{\mathrm{SS}}} = \frac{Q_{\mathrm{CC}}}{Q_I + Q_{\mathrm{CC}}}, Q_{\mathrm{CC}} = \frac{\beta}{1-\beta} Q_I \tag{4}$$

The value of β is related to the environment and structural characteristics of the component. In the design phase, the β value is initially estimated according to the component/system characteristics and IEC 61508-6 standard [20]. The estimation process and scoring correspondence range are shown in Fig. 2.

The estimation method and the calculation of the probability of common cause failure differ slightly depending on whether the failure is fully detectable or not. For systems where the failure is fully detectable the probability of common cause failure is:

$$Q_{\mathrm{CC}} = \beta Q_I \tag{5}$$

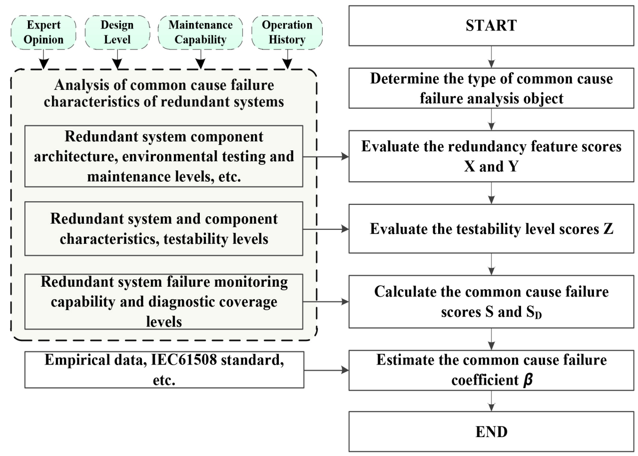

Figure 2. The process of estimation β value.

For systems where failure cannot be fully detectable, assuming that Q_{ID} is the probability of detected failure, Q_{IU} is the probability of undetectable failure, β_D is the coefficient of detectable common cause failure, and β_U is the coefficient of undetectable common cause failure, the probability of common cause failure of the system is:

$$Q_{\mathrm{CC}} = Q_{\mathrm{ID}} \beta_D + Q_{\mathrm{IU}} \beta_U \tag{6}$$

2.2.2 Non-Similar Redundant System

Since the component types of non-similar redundant systems are not identical, the method of estimating the common cause failure probability based on the system redundancy characteristic score is no longer applicable. Therefore, the square root model [21] is proposed to estimate the common cause failure probability of non-similar redundant systems.

Taking the redundant system composed of two different types of components A and B as an example, assume that the system common cause failure probability is $P(A_F \cap B_F)$, the failure probabilities of A and B are $P(A_F)$ and $P(B_F)$. Because the probability of common cause failure cannot be higher than the probability of failure of any one component, we can get:

$$[P(A_F \cap B_F)]_{\max} \leq min\{P(A_F), P(B_F)\} \tag{7}$$

Meanwhile, the probability of simultaneous failure of components A and B can be further decomposed into the probability of the other component failing again in case of failure of either component, we can get:

$$P(A_F \cap B_F) = P(A_F|B_F)P(B_F) \geq P(A_F)P(B_F) \tag{8}$$

$$[P(A_F \cap B_F)]_{\min} \geq P(A_F)P(B_F) \tag{9}$$

Let $a = P(A_F)P(B_F)$, $b = min\{P(A_F),P(B_F)\}$, approximate estimation of common cause failure probability from square root model is:

$$P(A_F \cap B_F) = \sqrt{\mathrm{ab}} \tag{10}$$

For the N of non-similar redundant systems, the square root model approach is generalised:

$$a = \prod_{i=1}^{N} P(A_i), b = \min\{P(A_1)......P(A_N)\},$$
$$P(\mathrm{CCF}) = \sqrt{\mathrm{ab}} \tag{11}$$

After calculating the common cause failure probability of non-similar redundant systems, the system comprehensive failure probability can be further calculated as follows:

$$P(Q_{\mathrm{SS}}) = \prod_{i=1}^{N} P(A_i\ ) + P(\mathrm{CCF}) \tag{12}$$

When there are both non-similar and similar redundancies in the system, it is necessary to further investigate the system failure probability by decomposing the system failure mode and considering the effects of different types of common cause failures.

3. Application and Analysis in MEA Electrical Power Systems

This section selects typical redundancy types in MEA electrical power systems analyse the common cause failure probability analysis methods and applications.

3.1 MEA Battery Common Cause Failure Analysis

The aviation batteries are an important part of the electrical power system. The front and rear electronic compartments each have a battery in B737 and B787 as shown in Fig. 3, which supplies power to critical flight instruments and navigation equipment in case of emergency to ensure the safe landing. Limited by design and production manufacturing defects, inadequate maintenance operations, high and low temperature vibration inside and outside the aircraft, two pieces of batteries may fail at the same time, threatening operational safety. The aviation battery owes the certain independence in each channel and does not have the functions of sensing, control and testing. Environmental tests, such as temperature, humidity, and EMC have been carried out before installation. According to IEC61508-6 standard and battery structure and test characteristics, the common cause failure score is shown in Table 1.

Calculate and get the common cause failure score of aviation battery $X = 17.5$, $Y = 23.5$, $Z = 0$, $S = 41$, and the estimated common cause failure factor is $\beta = 10\%$.

Statistical failure data of more than 50 aircraft power supply system between 2015 and 2018 of B737-800 from an airline [22], the failure rate of any battery is 0.208×10^{-5}/h, the rate of both batteries failing is 0.025×10^{-5}/h, using (1) to calculate and get $\beta^* \approx 12.02\%$, which is basically close to the β estimated by IEC61508-6. This analysis process and result can prove that the estimation method and the statistical method is reasonable and feasible, and the IEC61508-6 standard is suitable for aviation system.

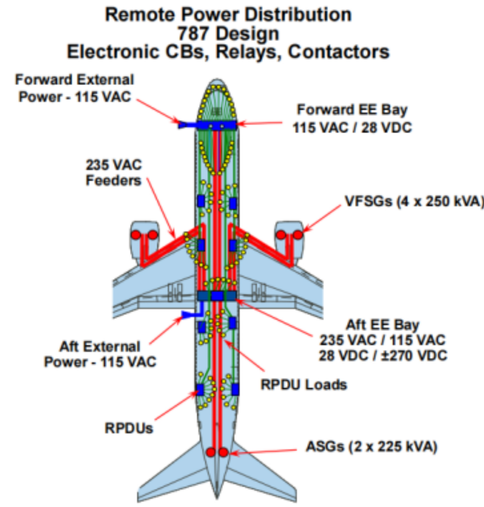

Figure 3. B787 battery mounting location.

3.2 MEA TRU Common Cause Failure Analysis

The B737 and B787 use tri-redundancy transformer rectifier units (TRU) to convert the AC power output from the on-board generators to DC power to meet the operational requirements of the equipment. The α values of different failure number [22] are analysed:

$$\alpha_1^{(3)} = 0.8690, \alpha_2^{(3)} = 0.0867, \alpha_3^{(3)} = 0.0443 \tag{13}$$

In response to the complex structure and weight of existing TRUs, the authors and their team proposed a highly reliable and low-weight TRU design method using half-bridge auxiliary circuits based on pulse multiplication [23]. The circuits of the ordinary and new TRU are shown in Fig. 4, and the main component parameters are listed in Table 2. The two types of TRU both convert the 115 V/360 Hz–800 Hz AC current output from the airborne generator to an airborne high voltage direct current of 270 V, and there is little difference in operability, additional circuitry, and other aspects. The performance of the new TRU meets the requirements of environmental tests, details of which can be found in [23].

The proposed new TRU failure rate and ordinary TRU failure rate are:

$$\lambda_{\mathrm{new}} = 0.6354 \times 10^{-6}/h, \lambda_{\mathrm{ordinary}} = 0.8381 \times 10^{-6}/h \tag{14}$$

The failure probability F of a single TRU approximately satisfies an exponential distribution parameterised by the failure rate:

$$F = 1 - e^{-\lambda t} \tag{15}$$

When part of the ordinary TRUs are replaced by the new TRUs, it is assumed that the causal factors of common cause failure, such as maintenance and operational environment are identical, which means the value of α-factor of common cause failure remains unchanged. The failure probability of TRU systems considering common cause failure is analysed after partial or total replacement.

Table 1
Aviation Battery Common Cause Failure Score

Item	Sensors and final elements	
	X_{SF}	$\mathrm{Y_{SF}}$
Separation/segregation		
Are all signal cables for the channels routed separately at all positions?	1	2
Complexity/design/application/maturity/experience		
Is the design based on techniques used in equipment that has been used successfully in the field for > 5 years?	1	1
Is there more than 5 years' experience with the same hardware used in similar environments?	1.5	1.5
Are inputs and outputs protected from potential levels of over-voltage and over-current?	1.5	0.5
Have the results of the failure modes and effects analysis or fault-tree analysis been examined to establish sources of common cause failure and have predetermined sources of common cause failure been eliminated by design?		3
Competence/training/safety culture		
Have designers been trained (with training documentation) to understand the causes and consequences of common cause failures?	2	3
Environmental control		
Is personnel access limited (for example locked cabinets, inaccessible position)?	0.5	2.5
Environmental testing		
Has the system been tested for immunity to all relevant environmental influences (for example EMC, temperature, vibration, shock, humidity) to an appropriate level as specified in recognized standards?	10	10

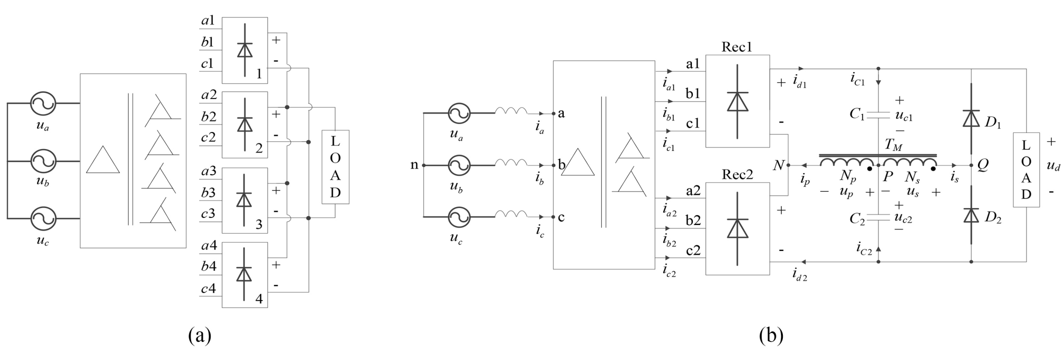

Figure 4. Circuits of the ordinary and new TRU: (a) the ordinary TRU and (b) the new TRU.

The failure model of tri-redundancy TRUs is decompose by fault tree. Let 1, 2, and 3 be different TRUs, and assume that two or three TRUs fail simultaneously by common cause failure, there are five system failure modes in total. $\boldsymbol{C}$ in Fig. 5 indicates the combination of different TRU common cause failure.

When one or more TRUs are replaced with new TRUs, the system failure mode of the tri-redundancy system is decomposed into three types of failure: three components fail independently one after another, two components fail by common cause and one fails independently at the same time, and three components fail by common cause. Non-similar redundant failure uses the square root model to estimate the common cause failure probability, and similar redundant failure combines with the α-factor to calculate the common cause failure probability. The tri-redundancy TRU failure probability is calculated as:

$$
\begin{aligned}
Q_{\mathrm{SS}} &= C_{123} + F_1F_2F_3 + C_{12}F_3 + C_{13}F_2 + C_{23}F_1 \\
C_{\mathrm{ij}} &= \begin{cases} \sqrt{\min\{F_i, F_j\} \bullet (F_iF_j)} & \text{Non} - \text{similar redundant} \\ \alpha_2^3 F_i & \text{Similar redundant} \end{cases} \\
C_{\mathrm{ijk}} &= \begin{cases} \sqrt{\min\{F_i, F_j, F_k\} \bullet (F_iF_jF_k)} & \text{Non} - \text{similar redundant} \\ \alpha_3^3 F_i & \text{Similar redundant} \end{cases}
\end{aligned} \tag{16}
$$

Table 2
Aviation Battery Common Cause Failure Score

	Ordinary TRU	New TRU
Weight	9.9 kg	5.34 kg
Consumed power	390 W	240 W
Basic price	9,500 yuan	13,500 yuan
Basic price: Only for basic device costs in laboratory		

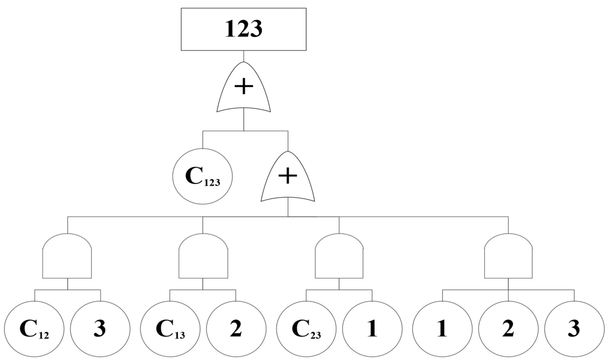

Figure 5. Fault tree of tri-redundancy TRU.

The system failure probability versus time for different types of tri-redundancy TRU systems obtained from the analysis is shown in Fig. 6, where ***N*** denotes a new type of TRU and ***O*** denotes an ordinary TRU.

According to the change curve of failure probability, when the working time is within 10,000 h, the failure probability of non-similar redundant systems is lower than that the similar redundant systems. With the increase of working time, the failure probability of non-similar redundant systems changes more significantly and gradually exceeds that of similar redundant systems, mainly because the common cause failure probability estimation of square root model is conservative. With two types of redundant systems, the greater the number of new TRUs with low failure rates, the lower the failure rate will the system owe.

To ensure that civil aircraft is safe, airlines will carry out comprehensive maintenance and inspection of aircraft at certain intervals to be able to eliminate potential safety risks in a timely manner. The maintenance interval for the B737, B787, and other aircraft types of extensive overhaul C inspection is roughly 4,000–8,000 flight hours.

According to the information in Table 2, the new TRU saves 0.15 kWh power per hour, and 600∼1,200 kWh power in the C inspection cycle. Based on that 5∼8 kWh electric energy is generated by a litre of aviation kerosene and the price of is 6∼8 yuan. Only from the perspective of electric energy saving, the new TRU could save 450∼1,920 yuan, which proves that replacing the partial TRUs is more affordable. According to the comprehensive device cost and safety level, in the C inspection time range, partial replacement of ordinary TRUs with new TRUs can improve system reliability while reducing equipment costs.

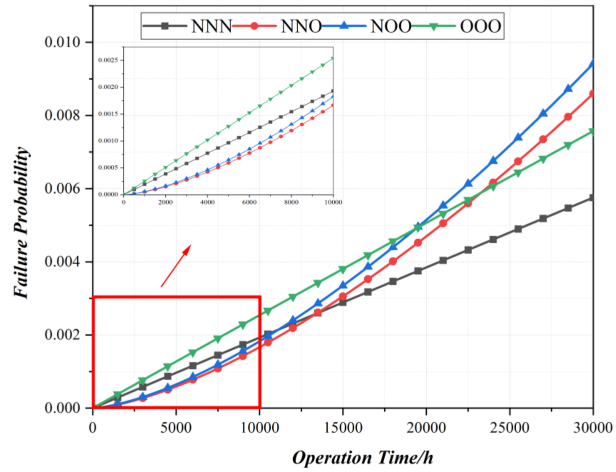

Figure 6. Tri-redundancy TRU failure probabilities for different combinations.

4. Conclusion

The comprehensive correction model of common cause failure probability is proposed for different types of redundant systems. Combined with MEA electrical power system, the application of the different algorithms is discussed and analysed. On the basis of this paper, we will further carry on the following work:

i) Analyse the possibility of simultaneous independent failure of components and further refine the system failure probability model.
ii) Considering the system common cause failure, the system optimisation of the system from multiple perspectives, such as system safety, economy, and structural and spatial constraints will be carried out further more.
iii) Considering the influence of maintenance and other factors on common cause failure, the system steady state availability and other indicators will be analysed.

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References

[1] A.V. Bogatyrev, V.A. Bogatyrev, and S.V. Bogatyrev, The probability of timeliness of a fully connected exchange in a redundant real-time communication system, *Proc. 2020 Wave Electronics and its Application in Information and Telecommunication Systems (WECONF)*, St. Petersburg, Russia, 2020, 1–4. DOI: 10.1109/WECONF48837.2020.9131517.

[2] Z.H. Dai, *Integrated design of aircraft electrical power supply system*, Doctoral Dissertation, Nanjing University of Aeronautics and Astronautics, Nanjing, China, 2020. DOI: 10.27239/d.cnki.gnhhu.2020.002612.

[3] Hamilton Sundstrand, Boeing 787 electrical system, 2011.

[4] Q. Wang, *Research on synchronous control system of dual-redundancy and dual motors*, Master Dissertation, Xi'an University of Science and Technology, Xi'an, China, 2021. DOI: 10.27397/d.cnki.gxaku.2021.000581.

[5] H.W. Jones, Common cause failures and ultra reliability, *Proc. 42nd International Conf. on Environmental Systems*, San Diego, California, 2012. DOI: 10.2514/6.2012-3602.

[6] P. Singh and L.K. Singh, Modeling and measuring common cause failures in measurement of reliability of nuclear power plant systems, *IEEE Transactions on Instrumentation and Measurement, 70*, 2021, 1–8. DOI: 10.1109/TIM.2021.3105265.

[7] Y. Cao, S. Liu, Z. Fang, and W. Dong, Reliability improvement allocation method considering common cause failures, *IEEE Transactions on Reliability, 69*(2), 2020, 571–580. DOI: 10.1109/TR.2019.2935633.

[8] Y. Zeng and Y. Sun, A reliability modeling method for the system subject to common cause failures and competing failures, *Quality and Reliability Engineering International, 38*(5), 2022, 2533–2547. DOI: 10.1002/qre.3089.

[9] V.C. Mathebula and A.K. Saha, Impact of quality of repairs and common cause failures on the reliability performance of intra-bay IEC 61850 substation communication network architecture based on Markov and linear dynamical systems, *IEEE Access, 9,* 2021, 112805–112820. DOI: 10.1109/ACCESS.2021.3104020.

[10] C. Wang and L. Xing, An explicit MDD-based method for common-cause failure analysis in phased-mission systems, *Proc. 2019 International Conf. on Quality, Reliability, Risk, Maintenance, and Safety Engineering (QR2MSE)*, Zhangjiajie, China, 2019, 655–661. DOI: 10.1109/QR2MSE46217.2019.9021181.

[11] M.J. Cannon, A.M. Keller, A. Pèrez-Celis, and M.J. Wirthlin, Modeling common cause failures in systems with triple modular redundancy and repair, *Proc. 2020 Annual Reliability and Maintainability Symposium (RAMS)*, Palm Springs, CA, USA, 2020, 1–6. DOI: 10.1109/RAMS48030.2020.9153662.

[12] J.R. Oliva, M.P. Ojeda, and J.S. Llanes, Integrated unavailability analysis including test degradation and efficiency, components ageing and common cause failures, *Annals of Nuclear Energy, 191*, 2023, 109920. DOI: 10.1016/j.anucene.2023.109920.

[13] H. Bao, H. Zhang, and T. Shorthill, Quantitative evaluation of common cause failures in high safety-significant safety-related digital instrumentation and control systems in nuclear power plants, *Reliability Engineering & System Safety, 230*, 2023, 108973. DOI: 10.1016/j.ress.2022.108973.

[14] K.N. Fleming, Reliability model for common mode failures in redundant safety systems, Technical Report GA-A-13284, U.S. Department of Energy Office of Scientific and Technical Information, United States, 1974. DOI: 10.2172/4206606.

[15] K.N. Fleming and A.M. Kalinowski, *An extension of the beta factor method to systems with high levels of redundancy*, (Washington, DC: Pickard, Lowe and Garrick, 1983).

[16] A. Mosleh, *A multi-parameter, event-based common cause failure model*, SMiRT9 Paper No. M7/3, 1987.

[17] J. Mi, N. Lu, Y.F. Li, H.Z. Huang, and L. Bai, An evidential network-based hierarchical method for system reliability analysis with common cause failures and mixed uncertainties, *Reliability Engineering & System Safety, 220*, 2022, 108295. DOI: 10.1016/j.ress.2021.108295.

[18] M.T. Haq, M. Zlatkovic, and K. Ksaibati, Assessment of tire failure related crashes and injury severity on a mountainous freeway: Bayesian binary logit approach, *Accident Analysis & Prevention, 145*, 2020, 105693. DOI: 10.1016/j.aap.2020.105693.

[19] Y.F. Li, *New methods of dynamic fault tree analysis of complex system and its application*, Doctoral Dissertation, University of Electronic Science and Technology of China, Chengdu, China, 2013.

[20] International Electrotechnical Commission, Functional safety of electrical/electronic/programmable electronic safety-related systems -Part 6: Guidelines on the application of IEC 61508-2 and IEC 61508-3, 2010.

[21] X. Jin, Y.J. Hong, and H.M. Du, *Reliability Analysis Method of Common Cause Failure System*, (National Defense Industry Press, 2008).

[22] X.F. Kong, J. Wang, and Z.M. Zhang, Reliability analysis of aircraft power system based on Bayesian networks and common cause failures, *Acta Aeronautica et Astronautica Sinica, 41*(5), 2020, 270–279.

[23] P. Kuangming, H. Yinxiao, L. Wenchen, S. Yanbo, P. Yichen, and G. Hongjuan, Safety analysis and test of a new 24 pulse transformer rectifier, *Proc. 2023 International Conf. on Power Energy Systems and Applications*, 2023, 836–841.

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