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Reliability modeling and optimization for satellite DC-DC converter under complex failure mechanism

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Abstract

The reliability of the power converter system, an essential energy adapter connecting solar panels and batteries in the satellite, is crucial to an entire satellite. This paper adopts a new fusing failure rate to build a more accurate model of reliability considering PPMS. In particular, the applicability of the new model is demonstrated to not only components following exponential distribution, but also to others following Weibull distribution. Furthermore, for the converter level, the Dynamic Fault Tree and Markov Process (MP) are utilized to model converter's reliability with the help of the state lumping method. In the case study, the reliability modeling of a dual Buck-Boost converter in satellite is conducted, as well as the optimization for redundancy design. The result indicates that the reliability of the converter in the satellite is more accurate and reasonable than that of using traditional methods.

Keywords: Periodic phased mission system, reliability modeling, Markov process, power converter.

1 Introduction

The satellite as a multi-state phased mission system is composed of electrical, optical, and mechanical subsystems. Among those subsystems, the reliability of electrical part plays a considerable role in entire system reliability [1-3], such as the power convert [4]. The reliability modeling of power converts in a satellite has several common features as follows [5-7]: 1. Hybrid form of energy supply. The electrical energy in a satellite derives from a hybrid source (battery, solar energy, etc.); 2. Phased missions. Generally, its reliability at the phase of launching, orbit transformation, or on-orbit operation is different due to the variable environment and mission; 3. Complex reliability model. Plenty of electronic components and their redundancies are included in a power converter, leading to the complexity of computation of system-level reliability.

There has been an increasing amount of literature on the reliability modeling of a phased mission system (PMS) recently, and meanwhile, several reliability models considering periodic missions have been developed. Xing studied the reliability of PMS considering ordered/unordered states [16] and internal/external effects [17]. Yu [18] explored the reliability of PMS considering inner phases and outer phases utilizing the Petri nets. Li analyzed the reliability of multi-state PMS employing a mixed redundancy strategy [19] and backup missions [20]. Wu [21] solved the reliability problem of multi states PMS as well as the reliability of phase switches. Li studied the reliability assessment for multi-state systems considering common cause failures based on the Fusion of Bayesian network, fuzzy probability[22] and proportional hazards model [23]. Regarding the modeling of periodic phased mission systems, Seo [24] investigated the reliability assessment of the unit that alternates between operation and standby states periodically, and finally achieved a system reliability model considering minimum maintenance. On this basis, Behboudi [25] realized the reliability estimation of system composed of periodically switching components. Wang [26] used the aggregated Markov to estimate the reliability of multi-operation level systems. Ermolin [27] studied a new failure rate formula to calculate the availability of periodically altering component, whose lifetime follows the exponential distribution. Unfortunately, that theory has some limitations because plenty of components do not follow the exponential distribution, and the applicability of proposed model was not discussed as well as the errors.

This paper investigates the modeling approaches for periodic and dynamic power electronics. On this basis, the component-level and system-level reliability modeling are studied. Taking a new and representative satellite power converter as an example, the proposed method is demonstrated by modeling the reliability of a satellite converter and optimizing its redundancy design. The main contribution of this work includes two aspects:

(1) Component-level reliability modeling. An enhanced mathematical derivation of the reliability model for PPMS is conducted based on not only the exponential distribution but also the Weibull distribution. Moreover, the applicability and sensitivity of proposed model are also proved.

(2) System-level reliability modeling. With the help of state-space lumping methods, the reliability model of a power converter is developed using the MPs. Furthermore, an optimization model for redundancy design is also developed to improve redundancy design.

2 Power converter

The power converter plays the role of voltage conversion between solar array and battery. To meet the voltage requirements of a wide range of solar arrays and bus bars, the power conversion system needs to adopt a Buck-Boost topology. In this research, the dual MOSFET Buck-Boost (DBB) topology is chosen. The element of a common DBB is shown in Fig. 1-a. The traditional DBB topology uses a two-mode control method: (1). if $U_{in} > U_o$, the satellite is in the P_2 phase, and the whole circuit is equivalent to a Buck converter (Q_1 in the on-off state, and normally off). (2). if $U_{in} \le U_o$, the satellite is in the P_3 phase, and the whole circuit is equivalent to a Boost converter (Q_1 on, and Q_2 in the on-off state).

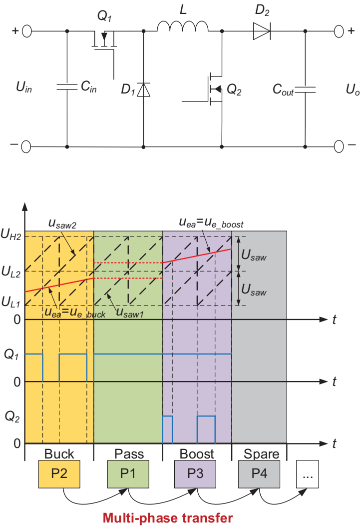


Fig. 1 Topology and work modes of DBB

3 Component-level reliability modeling

The basic failure rates λ_b for components are shown in Table 1, where: λ_b is the basic failure rate; θ_{stress} is the stress effect parameter; υ is the stress rate in each phase. The components C_{in1} and C_{in2} are given with the same parameters as they are similarly used for filtering, suffering from similar electronic stress, the same to D_1 and D_2. Q_1 and Q_2 have the same basic failure rates, but share differences in partial phase.

Table 1 Basic failure rates and phased stress details of BDD

Components	Failure mode	λ_b (10^{-6}/h)	υ	θ_{stress}			
				P1	P2	P3	P4
C_{in}, C_{out}	open	0.02	1.75	0.3	0.5	0.2	0
D	open	0.662	2.44				
L	open	0.471	1.61				

Q_1	open	1.932	2.15				
	short	0.518	2.15				
Q_2	open	1.932	2.15	0			
	short	0.518	2.15				

The change process of solar radiation is divided into 6 stages, assuming that the illumination intensity of solar radiation at any phase is constant, in line with the stress effect parameter θ_{stress}. The durations for each phase are obtained as shown in Fig. 2, where the period is 1.51 h.

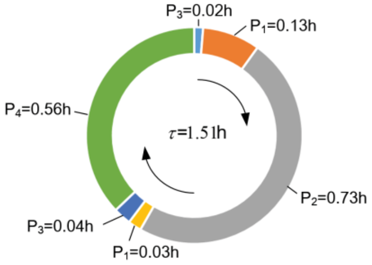


Fig. 2 The lasting time for each phase in one period

Based on the above information, 15 failure rates $\bar{\lambda}_i$ are modeled considering periodic phased missions according to Eq. (6), as shown in Fig. 3. To compare with traditional approaches, a new set of failure rates $\left\{\lambda_{i,\theta_{stress}=0.5}\right\}$ under constant loading stress $\theta_{stress}=0.5$ are also drawn in Fig. 3. As shown in Fig. 3, it is worth noting that $\bar{\lambda}_i$ is smaller than $\lambda_{i,\theta_{stress}=0.5}$, because $\bar{\lambda}_i$ contains more consideration that component i sometimes works under $\theta_{stress}\leq 0.5$. Furthermore, due to different working policies, $\left\{\bar{\lambda}_8,\bar{\lambda}_{10},\bar{\lambda}_{12},\bar{\lambda}_{14}\right\}$ share the same basic failure rates, but they are not equivalent, as well as $\left\{\bar{\lambda}_9,\bar{\lambda}_{11},\bar{\lambda}_{13},\bar{\lambda}_{15}\right\}$.

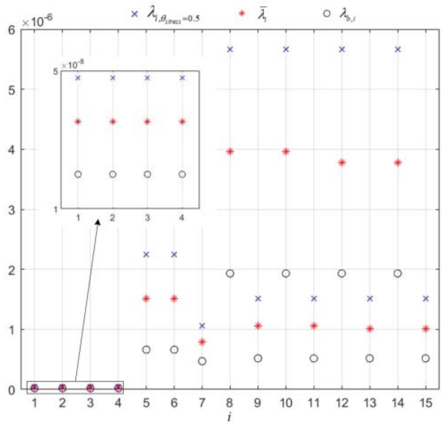


Fig. 3 Components failure rates ($\bar{\lambda}_i$) compared with basic ($\lambda_{b,i}$) and traditional ones ($\lambda_{i,\theta_{stress}=0.5}$)

4 System-level reliability modeling

Based the approximate failure rates $\bar{\lambda}_i$ of components in PPMS, the computation of system-level reliability of DBB would be convenient.. Divide the DFT of DBB into 3 modules, $\{M_1, M_2, M_3\}$, as shown in Fig. 4.

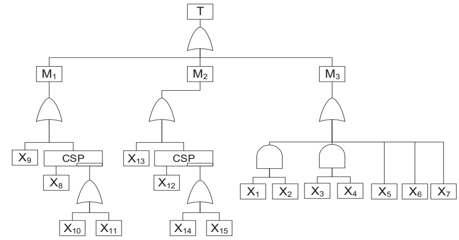
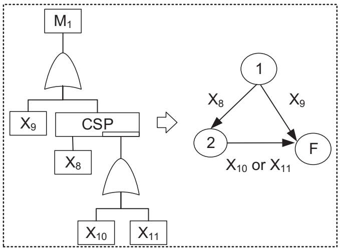


Fig. 4 Lumping for DFT of DBB

For M$_1$ and M$_2$, convert them to MP models as shown in Fig. 5.



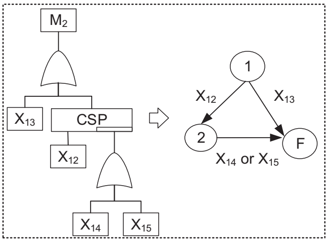


Fig. 5 MP models for M1 and M2

Let Eq. (1) be the transition matrix of M$_1$, where, $\lambda_{M_1\_o} = \overline{\lambda}_8 = \overline{\lambda}_{10}, \lambda_{M_1\_c} = \overline{\lambda}_9 = \overline{\lambda}_{11}$

$$Q_{M_1} = \begin{bmatrix} -\left(\lambda_{M_1\_o} + \lambda_{M_1\_c}\right) & \lambda_{M_1\_o} & \lambda_{M_1\_c} \\ 0 & -\left(\lambda_{M_1\_o} + \lambda_{M_1\_c}\right) & \lambda_{M_1\_o} + \lambda_{M_1\_c} \\ 0 & 0 & 0 \end{bmatrix}_{3\times 3} \tag{1}$$

The system-level reliability function of DBB can be obtained as,

$$R(t) = R_{M_1}(t) R_{M_2}(t) R_{M_3}(t) \tag{2}$$

The reliability function curve of $R(t)$ is shown in Fig. 6 in red color. The reliability considering periodic phased missions is also simulated by the Monte Carlo method to make a contrast, and the pseudocode is presented in table 2. In addition, to compare with the reliability computed traditionally without considering periodic phased mission, let $\theta_{stress} = 0.2$, $\theta_{stress} = 0.3$ and $\theta_{stress} = 0.5$, and several reliability curves with constant failure rates are also shown in Fig. 6. As a result, it can be found that the reliability calculation method proposed in this paper is very close to that using Monte Carlo method. The computation time of each method is presented in table 3, from which we can know the calculation cost of the proposed method is much lower than that of the Monte Carlo simulation.

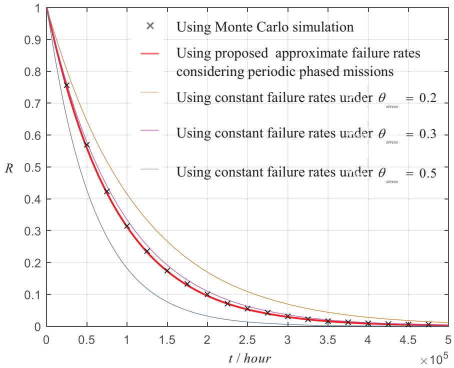


Fig. 6 Reliability of the proposed model compared to those without considering periodic phased missions

Table 2 Pseudocode of approximated reliability based on Monte Carlo simulation

```
Input: $F_{(i)}(x)$, the distribution of each event;
Output: $\tilde{R}(t)$, approximated reliability of periodic phased missions system.
    Step 1. for i=1: n: (n is the number of events)
        ● Generate 2e6 random numbers following the uniform distribution $U(0,1)$, $x_i^{(j)}$, where $1 \le j \le 2e6$.
        ● Based on the inverse distribution $F_{(i)}^{-1}(x)$, compute the random numbers of cumulative failure events.
Step 2. Calculate 2e6 numbers of the failure time for each event.
Step 3. for $k = 1:20$:
        ● let $t = 2500h*k$, and calculate the failure numbers of system every 2500 hours based on the DFT of DBB in Fig. 6, noted as $N(2500h \cdot k)$.
    Step 4. The reliability of the system can be approximately equal to: $\tilde{R}(2500h*k) = \frac{2e6 - N(2500h \cdot k)}{2e6}$.
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Table 3 Comparison of calculation time

Methods	Monte Carlo simulation	Proposed method	Traditional method (average)
Calculation time (s)	9.361	0.673	1.374

Computer information	CPU: AMD Ryzen 5 4500U 2.38 GHz; RAM: 16GB.

5 Optimization for redundancy design

Furthermore, the redundancy amount of components can be optimized via proposed method. If the redundancy numbers of Q_1, Q_2, C_{in}, and C_{out} are n_1, n_2, n_3, and n_4, based on the DFT and MP models, the transition matrix for M1 can be easily obtained under n_1 redundancies as,

$$\hat{Q}_{M_1}=\begin{bmatrix} -\left(\lambda_{M_1\_o}+\lambda_{M_1\_c}\right) & \lambda_{M_1\_o} & 0 & 0 & \lambda_{M_1\_c} \\ 0 & -\left(\lambda_{M_1\_o}+\lambda_{M_1\_c}\right) & \lambda_{M_1\_o} & 0 & \lambda_{M_1\_c} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & 0 & -\left(\lambda_{M_1\_o}+\lambda_{M_1\_c}\right) & \lambda_{M_1\_o}+\lambda_{M_1\_c} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{(n_1+2)\times(n_1+2)} \quad (3)$$

After a few simple inferences, the reliability function of M1 can be obtained as,

$$\hat{R}_{M_1}\left(t,n_1\right)=\exp\left(-(\lambda_{M_1\_o}+\lambda_{M_1\_c})t\right)\sum_{k=0}^{n_1}\frac{\left(\lambda_{M_1\_o}t\right)^k}{k!} \quad (4)$$

For M2, similarly, its reliability function can be obtained as,

$$\hat{R}_{M_2}\left(t,n_2\right)=\exp\left(-(\lambda_{M_2\_o}+\lambda_{M_2\_c})t\right)\sum_{k=0}^{n_2}\frac{\left(\lambda_{M_2\_o}\right)^k}{k!} \quad (5)$$

For M3, its reliability function is,

$$\hat{R}_{M_3}\left(t\right)=\left(1-\left(1-\exp(-\bar{\lambda}_1 t)\right)^{n_3+1}\right)\cdot\left(1-\left(1-\exp(-\bar{\lambda}_3 t)\right)^{n_4}\right) \quad (6)$$

So far, the reliability model $\hat{R}\left(t\right)=\hat{R}_{M_1}\left(t\right)\hat{R}_{M_2}\left(t\right)\hat{R}_{M_3}\left(t\right)$ is obtained under any redundancy design. Adding more design requirements, such as total cost or weight, and then an optimization model can be obtained. For example, let $\{5,5,1,1\}$ dollars be the prices of $\{Q_1, Q_2, C_{in}, C_{out}\}$ and 100000 hours be the minimum MTTF (Mean Time to Failure) of DBB, and then an optimization model can be built as,

$$\begin{cases} Min\ \ Cost_{Q_1,\,Q_2,C_{in},C_{out}}\left(n_1,n_2,n_3,n_4\right)=\sum_{i=1}^{4} n_i\cdot Cost_i \\ s.t.\ \ \ MTTF\left(n_1,n_2,n_3,n_4\right)\geq 100000h \end{cases} \quad (7)$$

where,

$$MTTF\left(n_1,n_2,n_3,n_4\right)=\int_0^\infty \hat{R}\left(t;n_1,n_2,n_3,n_4\right)dt=\int_0^\infty \hat{R}_{M_1}\cdot\hat{R}_{M_2}\cdot\hat{R}_{M_3}\cdot dt$$

The Enumeration method can be utilized to find the optimal solutio. For illustration purposes, assuming that n_1, n_2, n_3, and n_4 are less than 2, then there are 3^4 combinations of n_1, n_2, n_3, n_4, as shown in Table 4. Fig. 7 presents that dozens of combinations can meet the minimum $MTTF$ requirement (100000 hours), among those the lowest cost of those combinations is {2,2,1,1} with the minimum cost of 22 dollars, which is the optimal design.

Table 4 3^4 combinations of n_1, n_2, n_3, n_4

Serial	1	2	…	27	28	…	81
n_1	0	0	…	0	1	…	2
n_2	0	0		1	0		2
n_3	0	0		1	0		2
n_4	0	1		1	0		2

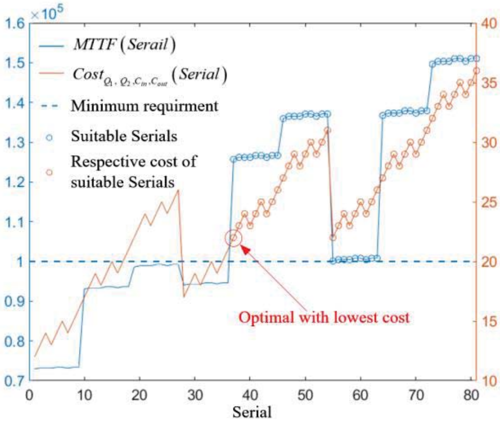

Fig. 7 Optimization for redundancy design of n_1, n_2, n_3, n_4

6 Conclusion

In this work, the reliability modeling method for DBB in satellites is investigated considering the effects of periodic phased missions in orbit. On one hand, a renewed failure rate based on periodic information for electronic component level is studied, as well as the statement of applicability and error which previous works have never covered. In addition, the applicability of the proposed model for modeling reliability of components of PPMS for not only exponential distribution but also Weibull distribution is demonstrated. On the other hand, the lumping method for DFT and MP model is also studied to mitigate the state space explosion and reduce computation complexity. Thus, a more credible reliability function and assessment for DBB is obtained, indicating that the traditional way of satellite power electronics seems to be not accurate. Finally, an efficient optimization model for redundancy design is also developed to optimize the number of redundancies.

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