Letters

Monte Carlo Simulation With Incremental Damage for Reliability Assessment of Power Electronics

Ariya Sangwongwanich, *Member, IEEE*, and Frede Blaabjerg, *Fellow, IEEE*

***Abstract*—Monte Carlo simulations have been widely used in the reliability assessment of power electronics systems. However, the conventional Monte Carlo simulation method is not directly suitable to be applied to the system with fault-tolerant operation, where the accumulated damage during the prefault operation needs to be taken into account as an initial damage during the postfault operation. To address this issue, a Monte Carlo simulation method based on incremental damage concept is proposed in this letter. The proposed method recursively accumulates the damage over time, making it possible to monitor the damage level of the individual sample when the failure occurs, and then being used as the initial damage during the postfault operation. Therefore, it can be applied to the power converters with fault-tolerant operation, which has been demonstrated with a case study of three-phase inverter having a fault-tolerant topology.**

***Index Terms*—Fault-tolerant inverters, lifetime, mission profiles, Monte Carlo methods, reliability.**

I. Introduction

FAILURE of power converter systems can have a severe consequence in terms of cost, but also compromise the safety of the overall system and operators. Accordingly, reliability assessment is a mandatory task during the design and development of the power converters in order to predict the expected failure rate (e.g., lifetime) of the key components and also the overall system failure rate in real applications [1]. This process usually involves a lifetime model [2], which represents the physic-of-failure of a certain failure mechanism (e.g., bond-wire fatigue and solder degradation). Initially, the estimation of lifetime and reliability of power electronics is based on a deterministic calculation of time-to-failure or cycle-to-failure for a certain loading/mission profile [3]–[5]. Later on, a statistical analysis, which represents uncertainty in the modeling process introduced by parameter variation, e.g., due to manufacturing tolerance, [6], [7] has also been included in the reliability analysis of power electronics systems [8], [9]. The abovementioned requirements are very suitable to be implemented using Monte Carlo simulation [10], and it has been widely adopted for the reliability assessment in power electronics applications [11]–[16].

The conventional Monte Carlo simulation, which has been employed in the previous research [11]–[16], is realized by modeling both the stress parameters (e.g., thermal cycling amplitude) and the lifetime model parameters with a certain distribution. Then, the lifetime estimation is carried out through multiple simulations with a population of n samples, where the parameters of each simulation are randomly selected from their distribution. By doing so, the accumulated damage of each sample can be calculated and converted into their corresponding time-to-failure, which represents the lifetime distribution of the components and usually follows the Weibull distribution with nonconstant failure rate characteristic [17], as it is illustrated in Fig. 1. However, the conventional Monte Carlo simulation is only suitable for a system with a single transitioning stage, e.g., from normal operation to failure, which so far has been considered in the previous studies (nonfault-tolerant power converters). This is due to the fact that the conventional Monte Carlo method cannot continuously monitor the damage evolution of each individual sample over time. Instead, it directly projects the time-to-failure of all the samples. For the system with multiple transitioning stages such as fault-tolerant power converters [18], the damage that has been accumulated during the prefault operation needs to be taken as an initial damage of the postfault operation [19]. Otherwise, the reliability assessment of the fault-tolerant system can be highly overestimated, since it assumes that all the components in the postfault configuration (that have survived the first failure) is as good as new, which may not be realistic due to the components' wear-out/aging. On the other hand, the conventional fault-tolerant reliability analysis based on Markov chain models cannot be directly applied to the Weibull distribution, which has nonconstant failure rate [20].

To address this issue, a Monte Carlo simulation method based on incremental damage concept is proposed in this letter. The proposed method enables a monitoring of the damage evolution of individual samples over time, making it possible to be implemented with power converters with multitransitioning stages (e.g., fault-tolerant operation).

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The authors are with the Department of Energy Technology, Aalborg University, DK-9220 Aalborg, Denmark (e-mail: ars@et.aau.dk; fbl@et.aau.dk).

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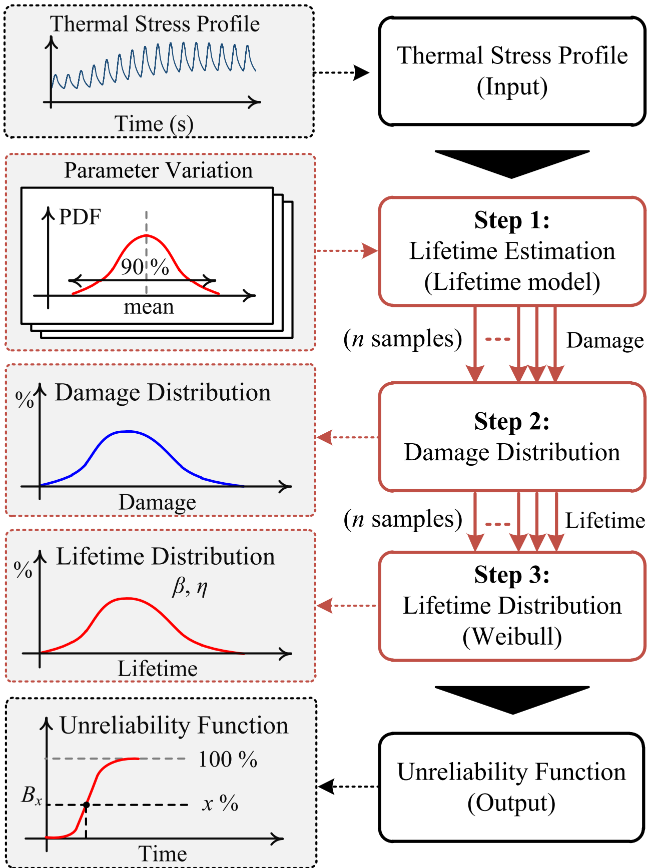

Fig. 1. Flow diagram of the conventional Monte Carlo simulation method applied to the reliability evaluation of power electronics systems.

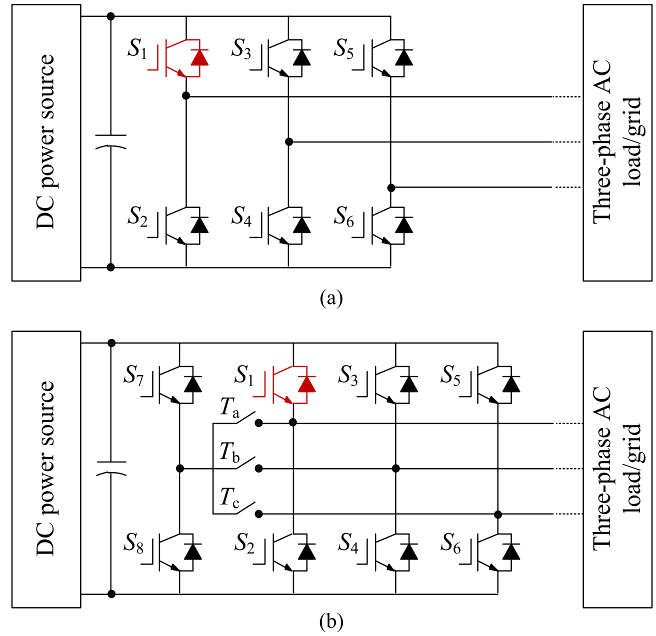

Fig. 2. System configuration of power converter with: (a) three-phase inverter topology (i.e., nonfault-tolerant) and (b) fault-tolerant inverter topology.

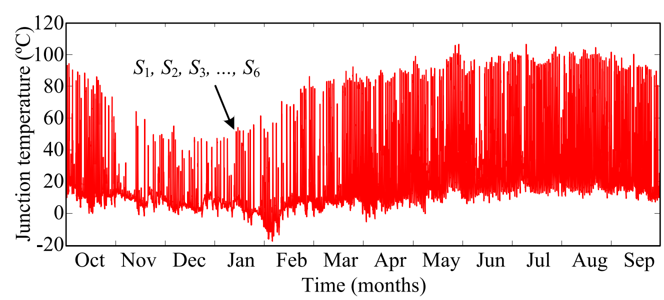

Fig. 3. Thermal stress of power devices during one-year operation.

II. Monte Carlo Based Reliability Assessment (Conventional Method)

A. Reliability Analysis

In the conventional Monte Carlo analysis, the lifetime estimation is carried out through multiple simulations with a population of n samples [12]–[16]. The stress and lifetime model parameters of each sample are modeled with a certain distribution, and they are randomly selected for each simulation following Fig. 1. It is crucial to select a distribution and a variation range that closely represents the parameter variation in real application. Typically, the variation of the lifetime model parameters can be obtained from the test results (represented as confidence interval), and they are normally provided by the manufacturer [2]. On the other hand, the variation of the stress parameters should be modeled according to the expected tolerance of the components [6], [7]. By doing so, the accumulated damage of each sample $AD(i)$ and their distribution (e.g., for n samples) can be obtained. Since the accumulated damage $AD(i)$ indicates a proportion of lifetime that has been consumed for the i^{th} sample under the applied mission profile, the lifetime (i.e., time-to-failure) of each sample $L(i)$ can be obtained as

$$L(i) = \left\lfloor \frac{1}{AD(i)} \right\rfloor \quad (1)$$

where the lifetime $L(i)$ indicates how many times (periods) a mission profile can be applied until the failure occurs (e.g., $L(i) = 10$ years if $AD(i) = 0.1$ per year).

Afterwards, the lifetime distribution for all samples can be obtained, while its cumulative function is referred to as the unreliability function, which indicates the increase in the failure population over time. The failure criterion is usually selected based on the B_x lifetime, which is the time when $x\%$ of population has failed (e.g., B_{10} lifetime).

B. Case Study With Nonfault-Tolerant Systems

The conventional Monte Carlo based reliability assessment method will be demonstrated for a three-phase inverter shown in Fig. 2(a), which represents a nonfault-tolerant inverter system. The thermal stress profile of each power device during a one-year mission profile is shown in Fig. 3, which are the similar for all power devices due to their equal average power losses. In this case, a population of 10 000 samples is used in the Monte Carlo simulation, and the failure criterion is selected as B_{10} lifetime of the power device.

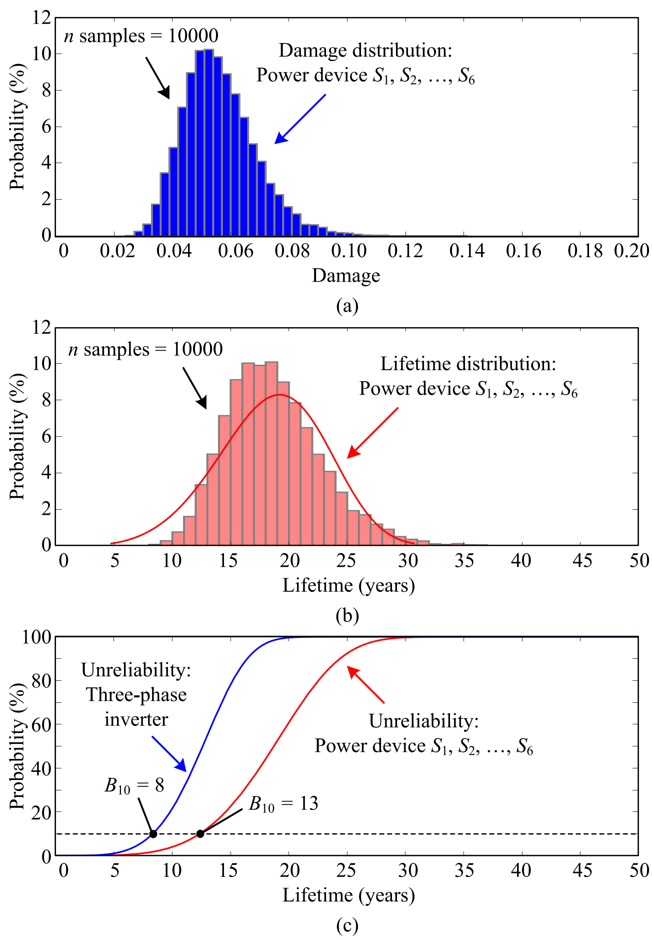

Fig. 4. Reliability analysis of three-phase inverter with the conventional Monte Carlo simulation method: (a) accumulated damage distribution, (b) lifetime distribution, and (c) unreliability function.

The distribution of the accumulated damage over the mission profile period (e.g., 1 year) is illustrated in Fig. 4(a). Following (1), the lifetime of each sample can be obtained, as shown in Fig. 4(b). Then, the unreliability function of the individual power device (e.g., component level) can be obtained, as shown in Fig. 4(c). Moreover, the unreliability of the entire three-phase inverter, which is a system level with six power devices, can also be calculated from the component-level unreliability by using a reliability block diagram, as it is also shown in Fig. 4(c). In this case, the B_{10} lifetime of the power device is 13 years, as it is illustrated in Fig. 4(c), which indicates that a failure may occur to one of the power devices after 13 years of operation.

C. Limitations in Fault-Tolerant Systems

The main drawbacks of the conventional Monte Carlo simulation is its lack of ability to determine the status (e.g., damage level) of the survivor samples when a certain amount of samples has failed. This is due to the direct projection of time-to-failure of each individual sample using (1), e.g., from Fig. 4(a) to (b). For instance, assuming that the power device S_1 fails after 13 years of operation following the B_{10} lifetime in Fig. 4(c), it is not possible to determine the damage level of the other five power devices (which survive the failure) at the time the failure occurs. In that case, the conventional Monte Carlo simulation cannot be applied to the systems with multiple transitioning stages such as fault-tolerant power converters, where the damage occurred during the prefault operation (of the survivor components) needs to be taken into account as an initial damage during the postfault operation.

III. Proposed Monte Carlo Analysis With Incremental Damage

A. Incremental Damage

The proposed Monte Carlo simulation method is based on the incremental damage concept. In this approach, the accumulated damage of each sample is recursively increased over each mission profile period. Thus, the accumulated damage of each sample is time-dependent $AD(i,t)$ following:

$$AD(i,t\!=\!kT_{\text{MP}})\!=\!AD(i,t\!=\!0)+k\cdot AD(i,t\!=\!T_{\text{MP}}) \quad (2)$$

where the first and second terms represent the initial and the incremental damage, respectively. T_{MP} is the mission profile period (e.g., $T_{\text{MP}} = 1$ year) and k is an integer, which represents the number of mission profile period that has been applied. Notably, in this case, a linear accumulation of damage is assumed, which is usually the case for thermo-mechanical fatigue analysis following Miner's rule [21]. Nevertheless, the expression in (2) can also be applied to a nonlinear damage accumulation as well by modifying the incremental damage term to be nonlinear.

Then, the lifetime (e.g., time-to-failure) of each sample $L(i)$ can be calculated as

$$L(i) = k_{\min}T_{\text{MP}}, \text{when } AD(i,\ t = k_{\min}T_{\text{MP}}) \geq 1 \quad (3)$$

where $k_{\min}$ is a minimum integer that fulfills (3). The lifetime $L(i)$ in (3) is the time instant when the accumulate damage AD just reaches 1 (i.e., when the failure occurs).

B. Numerical Example

The concept of the proposed Monte Carlo simulation method is demonstrated by using a numerical example. It is assumed that the accumulated damage of ten samples during one-year operation is

$$AD(i,\ t = 1 \text{ year}) = [0.05, 0.05, 0.10, 0.10, 0.10, 0.20, 0.20, 0.25, 0.30, 0.40].$$

Then, the accumulated damage of the following years can be obtained, as shown in Fig. 5. It can be noticed from Fig. 5(c) that after three years, one sample (whose $AD = 1.2$) will fail (i.e., $B_{10} = 3$ years). The same process can be repeated until all the samples have failed (e.g., $AD \geq 1$), and the lifetime of each sample $L(i)$ can be calculated from (3) as

$$L(i) = [20, 20, 10, 10, 10, 5, 5, 4, 4, 3]$$

which is identical to the results obtained from the conventional Monte Carlo simulation method in (1).

However, the proposed method can monitor the damage evolution of each individual sample overtime, as it has been

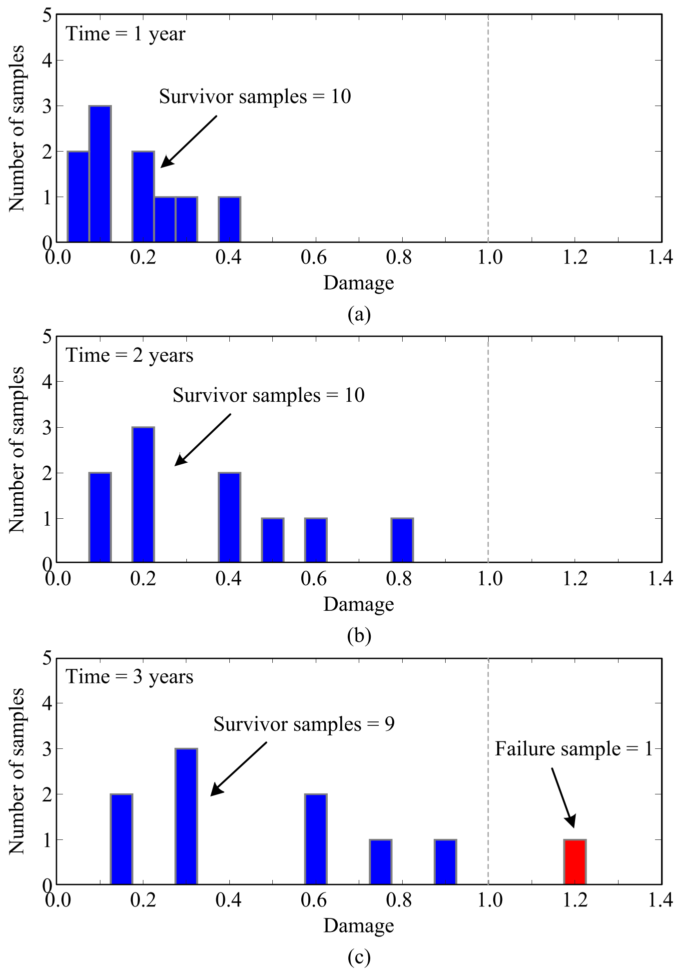

Fig. 5. Time-dependent accumulated damage of ten samples using the Monte Carlo simulation with incremental damage after: (a) one year; (b) two years; and (c) three years of operation.

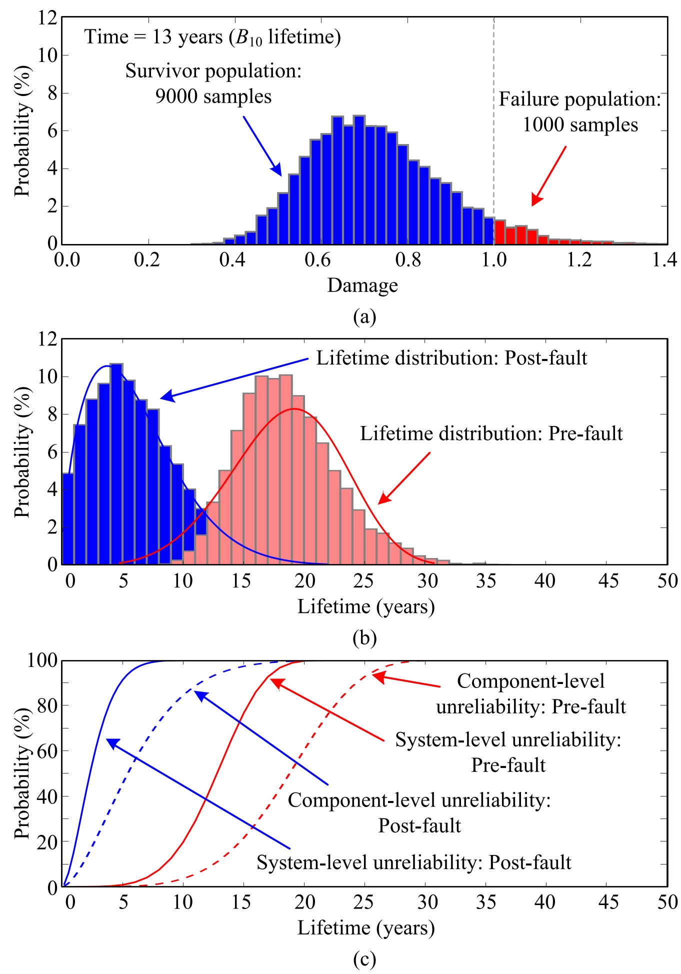

Fig. 6. Reliability analysis of fault-tolerant inverter with the proposed Monte Carlo simulation method: (a) accumulated damage distribution; (b) lifetime distribution; and (c) unreliability function.

demonstrated in Fig. 5. In that case, when a certain proportion of a sample has failed (e.g., 10% at $t = 3$ years), the damage status of the other samples when the failure occur can be calculated. Thus, if a fault-tolerant strategy is applied, the initial damage of the postfault operation can be obtained from $AD(i,\ t = 3 \text{ years})$.

IV. Reliability Assessment With Fault-Tolerant Power Converters Systems

The proposed Monte Carlo simulation method is applied to the fault-tolerant inverter topology in Fig. 2(b), where the system can be divided into the two operating stages as discussed in the following.

A. Prefault Operation

In the prefault operation, the operation of the fault-tolerant inverter is identical to the three-phase inverter in Fig. 2(a). Therefore, the accumulated damage distribution is identical to that in Fig. 4(a). By applying the proposed Monte Carlo simulation method, the damage is recursively increased on the yearly basis. A snapshot of the accumulated damage when $AD(i,\ t = 13 \text{ years})$ is shown in Fig. 6(a), where it can be seen that 10% of the samples have already failed at this point. In other words, this is the time instant when one of the power devices is expected to fail according to the B_{10} lifetime criterion. This process can keep repeating until all the samples reach its end-of-life, and the corresponding lifetime distribution of the prefault operation is, as shown in Fig. 6(b).

B. Postfault Operation

When the fault occurs, e.g., at $t = B_{10}$, the postfault configuration can be applied by first isolating the leg with the faulty power device (e.g., phase a when S_1 fails). Then, the redundant leg (e.g., S_7 and S_8) is connected to the load of the faulty phase (e.g., phase a) through the relay T_a.

During the postfault configuration, the initial damage of the power devices that have survived the failure (e.g., S_3, S_4, S_5, and S_6) is taken from the accumulated damage when the fault occurs $AD(i,\ t = B_{10})$. Thus, the accumulated damage during postfault operation will reach 1 relatively fast. This is reflected in the lifetime distribution during postfault operation in Fig. 6(b). A comparison between the unreliability function of the prefault and postfault operation is shown in Fig. 6(c).

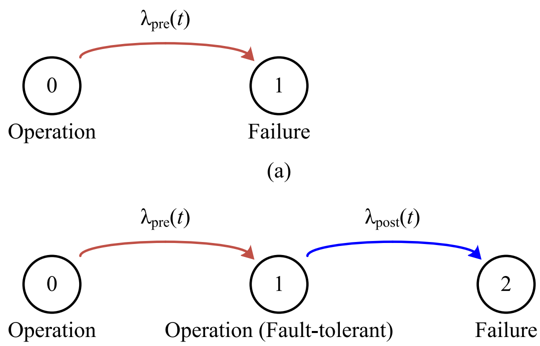

Fig. 7. Markov Chain model of: (a) three-phase inverter and (b) fault-tolerant inverter, where $\lambda_{\text{pre}}(t)$ and $\lambda_{\text{post}}(t)$ are the prefault and postfault failure rate.

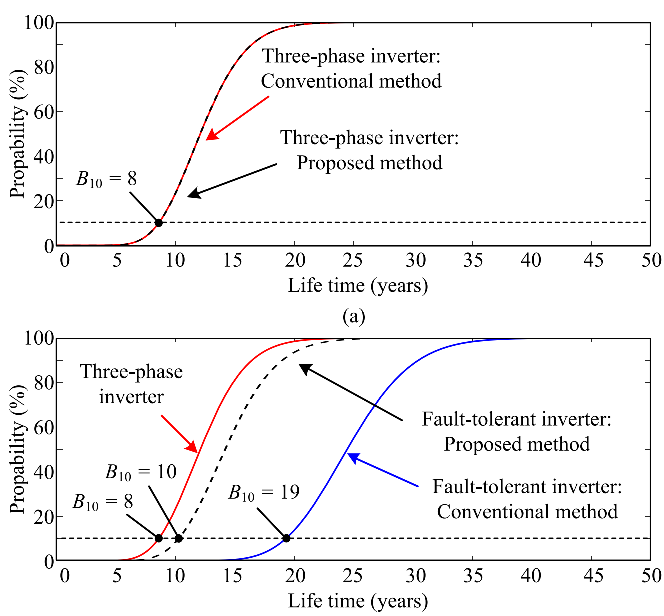

Fig. 8. Comparison between the reliability evaluation using the conventional and the proposed Monte Carlo simulation methods with: (a) three-phase inverter topology (i.e., nonfault-tolerant); and (b) fault-tolerant topology.

C. Reliability Analysis

The unreliability function in Fig. 6(c) can be used for calculating the failure rate and the overall system-level reliability during the entire operation (prefault and postfault operation), e.g., using the Markov chain model. Two different inverter topologies: three-phase inverter (nonfault-tolerant) and fault-tolerant inverter in Fig. 2 are considered to demonstrate the effectiveness of the proposed method. The Markov chain model (e.g., state transition diagram) of the two topologies are demonstrated in Fig. 7, where $\lambda_{\text{pre}}(t)$ and $\lambda_{\text{post}}(t)$ are the system-level failure rate (with Weibull distribution function) during the prefault and postfault conditions, respectively.

The unreliability of the three-phase inverter (i.e., nonfault tolerant) when using the conventional and proposed methods is shown in Fig. 8(a). It can be observed that both methods provide similar reliability evaluation results. However, a significant difference in the reliability evaluation results can be seen in Fig. 8(b) when the conventional and proposed methods are being applied to the fault-tolerant inverter topology. In that case, the conventional method results in an overestimation of the reliability improvement, where the B_{10} lifetime is more than double, since it assumes the same (un)reliability function during the prefault and postfault operation. However, it is obvious from the results in Fig. 6(a) that a majority of the population has already reached a certain level of accumulated damage when the fault occurs. Thus, by taking this aspect into consideration with the proposed method, the expected B_{10} lifetime improvement from fault-tolerant operation is only two years for this case study.

Accordingly, the proposed Monte Carlo simulation based on incremental damage method can generally be applied to evaluate the reliability of both nonfault-tolerant and fault-tolerant topologies (without overestimating the reliability improvement). Moreover, it can also be applied to other system topologies and component technologies such as wide band-gap power devices as well.

V. Conclusion

This letter has proposed a Monte Carlo simulation method based on incremental damage concept. The proposed method enables a monitoring of the damage evolution over time, making it possible to be applied for reliability assessment of power electronics systems with fault-tolerant operation, which is the limitation of the conventional method. A case study of reliability assessment with fault-tolerant inverters has been carried out, where the accumulated damage during the prefault was taken into consideration as the initial damage during postfault operation, resulting in a more accurate reliability estimation of fault-tolerant inverters subjected to wear-out/aging.

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