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Reliability Assessment of Fault-Tolerant Power Converters including Wear-Out Failure

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***Abstract*—Conventionally, reliability analysis of fault-tolerant (FT) power converters is carried out using a Markov Chain (MC) model, which is only applicable for components with a constant failure rate. However, modern power electronics are expected to operate even until the components start to wear-out, e.g., due to aging/degradation, where the failure rate of the components is no longer constant, and thus the traditional MC model cannot be applied. To address this issue, a method to evaluate the reliability of FT power converters considering wear-out failure is proposed in this paper. The proposed solution employs the method of stages to incorporate the wear-out failure states in the MC model, which includes the failure rates during pre-fault and post-fault conditions. By doing so, the wear-out failure can be taken into account in the reliability analysis of FT power converters, which has been demonstrated with a case study of a three-phase inverter with FT topology for PV application.**

***Index Terms*—Reliability, lifetime, fault-tolerant inverters, wear-out failure, Markov Chain model, Method of stages.**

I. Introduction

Reliability is an important aspect in the design of power converters, since it can significantly affect the operation and maintenance cost, but also safety aspects. In mission/safety-critical applications such as electric vehicles, railways, and aircrafts, an interruption due to failure of components in power converters is usually not acceptable due to the safety and risk concerns [1]–[3]. In those cases, fault-tolerant (FT) operation is a common solution to ensure (or improve) the reliability of the power converters, which can be implemented as a redundant unit or system/topology reconfiguration [4]–[6].

In the past, it was widely assumed that the reliability of the power electronics components such as Insulated-Gate Bipolar Transistor (IGBT) can be modeled with a constant failure rate based on handbook/statistical data (e.g., MIL-HDBK-217F) [7]. This implies that the useful life (i.e., operating period) of the components in the power converters is limited to the constant failure rate region of the well-known bathtub curve [8], where random failures and catastrophic failures are dominant, as it is illustrated in Fig. 1. However, the advancement and increased maturity in the power electronics technology as well as a pressure to minimize the cost have extended the operational boundary of the modern power converters further towards the wear-out region in the bathtub curve [9]–[11]. In that case, a majority of failures will occur when the components are entering into the wear-out period. Therefore, the reliability evaluation of the power converters also needs to consider the wear-out period where the failure rate of the component $\lambda(t)$ is not constant, but increasing over time, as it is shown in Fig. 1.

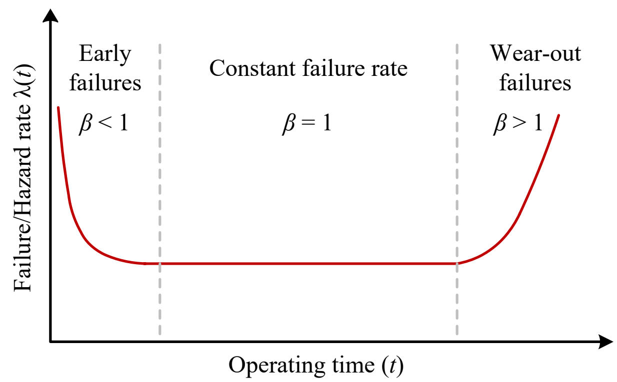

Fig. 1. The bathtub curve which represents the typical failure rate characteristic of the component during operation, where three failure rate characteristics (e.g., early failures, constant failure rate, and wear-out failures) can be represented with Weibull distribution using different shape parameters β.

In the previous research, the reliability analysis of fault-tolerant power converters is carried out using a Markov Chain (MC) model [2], [3], which represents the power converter in several states together with the probability of transition between states as shown in Fig. 2. One main constraint of the MC model is that the probability of transitioning between states (i.e., failure rate) is constant, e.g., $\lambda(t) = \lambda$ [12]. While this constraint is aligned with the assumption of constant failure rate of power converters in the past (e.g., in the middle phase of the bathtub curve), the same condition is not applicable for modern power converters whose useful life is expected to cover also the initial phase of the wear-out period [13]. Thus, it is not possible to apply the traditional MC model for analyzing the reliability of FT power converters when wear-out failures are considered

To address this issue, a reliability evaluation method for FT power converters considering wear-out failures is proposed in this paper. The proposed method employs the method of stages to incorporate the wear-out failures into the MC model. By doing so, it is possible to include the impact of component's wear-out into consideration in the reliability analysis of the FT power converters. The rest of this paper is organized as follows: the FT operation of the power converter is described in Section II, where the typical FT topology

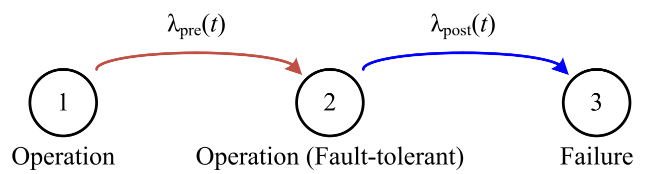

Fig. 2. Proposed reliability evaluation method based on Markov Chain model applied to fault-tolerant power converter with non-constant failure rates (i.e., $\lambda_{\text{pre}}(t)$ and $\lambda_{\text{post}}(t)$).

for three-phase inverter is considered as an example. The conventional reliability assessment method and its limitation is also discussed in this part. In Section III, a method to include the wear-out failure into the reliability analysis of the FT system based on the method of stages is introduced. A case study to demonstrate the application of the proposed method is carried out in Section IV, where the FT power converter for PV application is considered. Finally, concluding remarks are provided in Section V.

II. Fault-Tolerant Operation of Power Converter

In this section, the topology of FT power converter for three-phase inverter is discussed. The system configurations during pre-fault and post-fault operations are demonstrated together with the conventional reliability modeling method based on MC model with constant failure rate.

A. Topology

In this paper, the two-level three-phase inverter shown in Fig. 3(a) is considered as an example, since it is one of the most commonly used topologies for DC-AC conversion. Several topologies have been proposed to provide FT capability for the three-phase inverter in Fig. 3(a) such as the switch-redundant [14], [15], the double-switch-redundant [16], and the phase-redundant [17] topologies. Among different FT solutions, the phase-redundant topology shown in Fig. 3(b) is one of the most commonly used solutions in practical applications due to its advantages such as maintaining the same component rating and post-fault power rating factor as in normal operation. It has also a wide range of fault coverage with the trade-off of number of components and cost.

B. System Configuration

The system configuration of a phase-redundant topology in Fig. 3(b) can be divided into three operating states. During the normal operation, the redundant phase is isolated by the auxiliary switches (i.e., T_{a}, T_{b}, and T_{c}), and the system configuration is identical to the three-phase inverter in Fig. 3(a). When a failure occurs in one of the power devices, the phase with the faulty power device needs to be isolated. Then, the redundant phase is connected to the load of the faulty phase by the auxiliary switch following Fig. 4. Notably, the gate driving signals need to be re-routed from the faulty phase to the redundant phase. In case another failure occurs in one of the remaining power devices, as it is illustrated in Fig. 4(c),

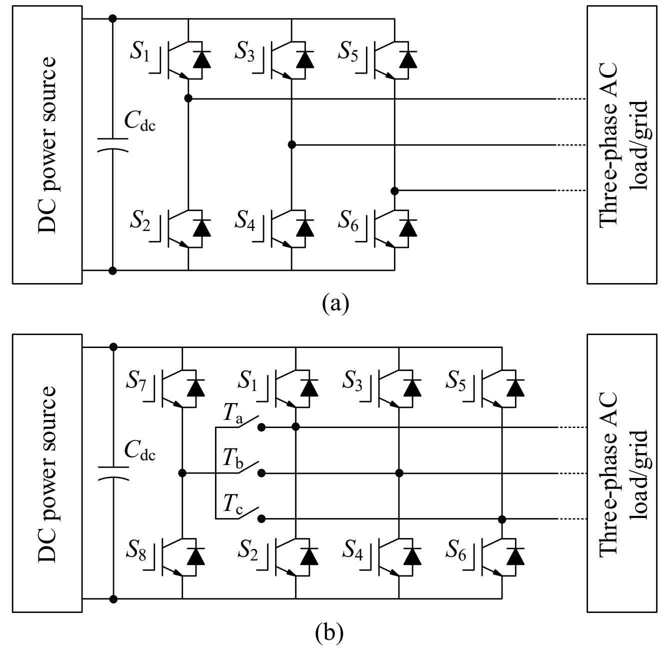

Fig. 3. System configuration of power converter with: (a) three-phase inverter topology (i.e., non fault-tolerant) and (b) phase-redundant fault-tolerant inverter topology, where S_x is the switching power device (e.g., IGBT) and T_x is the auxiliary switch (e.g., relay or TRIAC).

the power converter can no longer supply the three-phase load and the system is considered to be in the failure state following the MC model in Fig. 2.

C. Conventional FT Analysis and Its Limitations

In the conventional method, the reliability of FT power converters is modeled with the MC model, where each state in the MC model represents each system configuration, e.g., pre-fault operation, post-fault operation, and failure. For instance, the FT power converter with three system configurations in Fig. 4 can be easily constructed into three-state MC model as it has been shown earlier in Fig. 2. One important constraint when applying the MC model is that the failure rate between each state is constant, e.g., $\lambda(t) = \lambda$. This is applied to the system whose failure density function $f_{\text{exp}}(t)$ follows an exponential distribution as

$$\begin{aligned} f_{\text{exp}}(t) &= \lambda \exp(-\lambda t) \\ \lambda_{\text{exp}}(t) &= \frac{f_{\text{exp}}(t)}{\int_t^{\infty} f_{\text{exp}}(t)dt} = \lambda \end{aligned} \tag{1}$$

where it can be seen from (1) that the failure rate $\lambda_{\text{exp}}(t)$ of the exponential distribution is constant.

Assuming a constant failure rate, i.e., $\lambda(t) = \lambda$, the MC model of the FT power converter in Fig. 2(a) can be constructed with the following state equations

$$\begin{bmatrix} \dot{P}_1(t) \\ \dot{P}_2(t) \\ \dot{P}_3(t) \end{bmatrix} = \begin{bmatrix} -\lambda_{\text{pre}} & 0 & 0 \\ \lambda_{\text{pre}} & -\lambda_{\text{post}} & 0 \\ 0 & \lambda_{\text{post}} & 0 \end{bmatrix} \cdot \begin{bmatrix} P_1(t) \\ P_2(t) \\ P_3(t) \end{bmatrix} \tag{2}$$

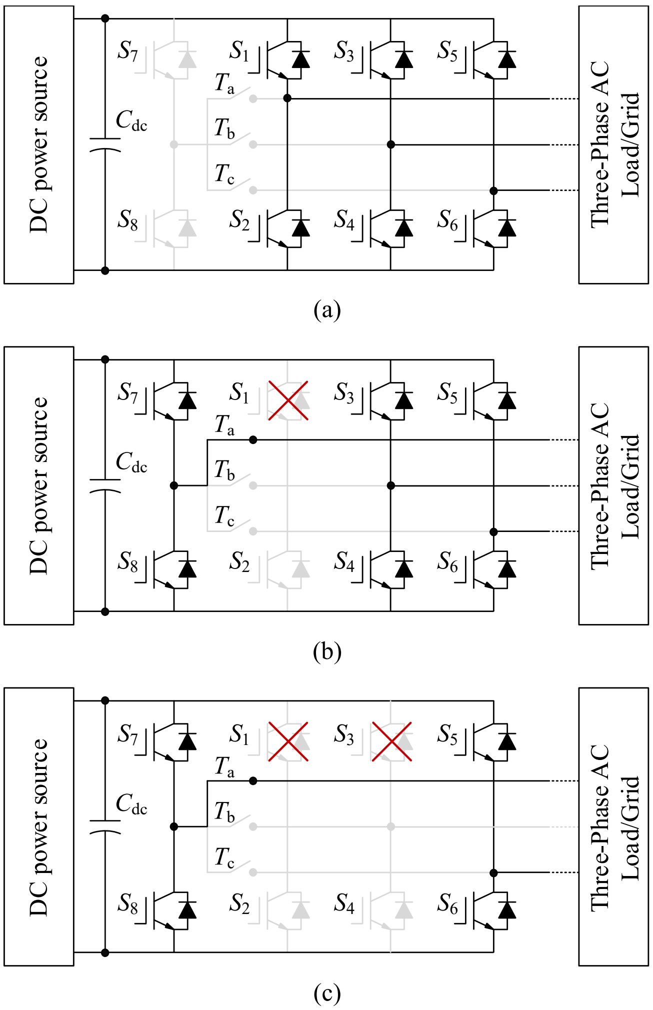

Fig. 4. System configuration of fault-tolerant power converter with phase-redundant topology during: a) normal operation (i.e., pre-fault operation), b) fault-tolerant operation (i.e., post-fault operation), and c) failure, where S_x is the switching power device (e.g., IGBT) and T_x is the auxiliary switch (e.g., relay or TRIAC).

By solving the state equations in (2), the obtained time-dependent probability of the system being in State 1 $P_1(t)$, State 2 $P_2(t)$, and State 3 $P_3(t)$ corresponds to the probability that the power converter will be in normal operation, FT operation, and failure, respectively. Since the power converter is in operation when the system is in either State 1 or State 2, the reliability of the FT power converter $R(t)$ can be determined as the following

$$R(t) = P_1(t) + P_2(t) = 1 - P_3(t). \tag{3}$$

However, the fundamental requirement of the MC model is that the failure rate is constant, i.e., $\lambda(t) = \lambda$. From the bathtub curve in Fig. 1, this corresponds to the period where $\beta = 1$. On the other hand, the wear-out failure, which represents an increasing failure rate with $\beta > 1$ as shown in Fig. 1, cannot be directly applied to the (conventional) MC model. Thus, a new method is required to analyze the reliability of FT power converters during the wear-out period.

III. Reliability Analysis of Fault-Tolerant Systems with Wear-Out Failure

In this section, a method to incorporate the wear-out failure (i.e., non-constant failure rate) to the reliability analysis of FT power converter based on MC model will be presented.

A. Wear-Out Failure

During the wear-out period, the failure rate of the component is increasing over time. This characteristic is usually well represented with the Weibull distribution [18], whose failure density function $f_{\text{wb}}(t)$ and failure rate $\lambda_{\text{wb}}(t)$ can be represented by two parameters given as

$$f_{\text{wb}}(t) = \frac{\beta t^{\beta-1}}{\eta^{\beta}} \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \tag{4}$$

$$\lambda_{\text{wb}}(t) = \frac{\beta t^{\beta-1}}{\eta^{\beta}} \tag{5}$$

where β is the shape parameter and η is the scale parameter. The shape parameter β represents the failure mode of the component, where the components that have experienced the same failure mode/mechanism will have similar shape parameter β. The scale parameter η corresponds to the time when 63.2 % of a population will have failed.

When analyzing (5), it can be noticed that the failure rate of all three regions in the bathtub curve in Fig. 1 can be represented by the Weibull distribution with different shape parameters β. In fact, the failure rate of the exponential distribution in (1) is a just special case of the Weibull distribution where $\beta = 1$. For the wear-out failure, the shape parameter of the Weibull distribution is $\beta > 1$, representing an increasing failure rate over time.

B. Method of Stages

Since the failure rate of the Weibull distribution in (5) is no longer constant (except the case when $\beta = 1$), the conventional MC model discussed in (2) cannot be directly applied to analyze the wear-out failure of the FT power converter. In order to solve this issue, a method of stages was proposed to incorporate a non-constant failure rate in the MC model [19]. It has been demonstrated in [12] that the failure rate with Weibull distribution in Fig. 5(a) can be represented by a series combination of multiple states with an exponential failure rate, as it is shown in Fig. 5(b). If all the q states (with exponential distribution) which are connected in series are identical (e.g., with the same failure rate p), the total failure density function of the series combination in Fig. 5(b) becomes the Special Erlangian distribution $f_{\text{se}}(t)$ [12] as

$$f_{\text{se}}(t) = \frac{p(pt)^{q-1}}{(q-1)!} \exp(-pt) \tag{6}$$

where p is the failure rate of each exponential state and q is number of states connected in series.

In order to represent the Weibull distribution with the Special Erlangian distribution, the first and the second moments of the two distributions need to be identical [12]. From (6), the

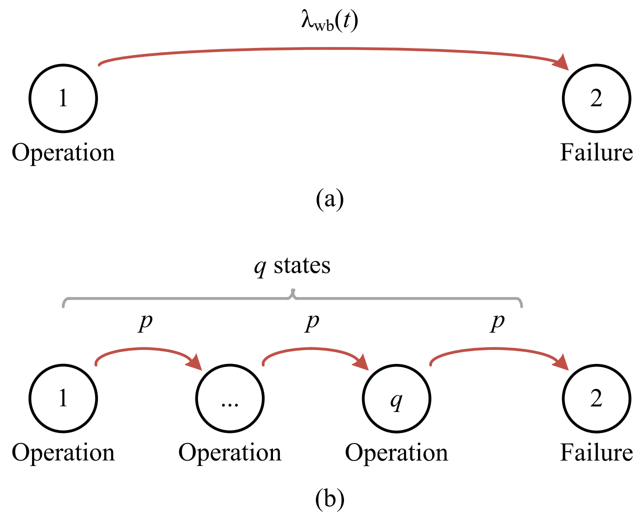

Fig. 5. Markov Chain model of non fault-tolerant power converter represented by: a) Weibull distribution failure rate $\lambda_{\text{wb}}(t)$ and b) method of stages with q states with exponential distribution failure rate of p.

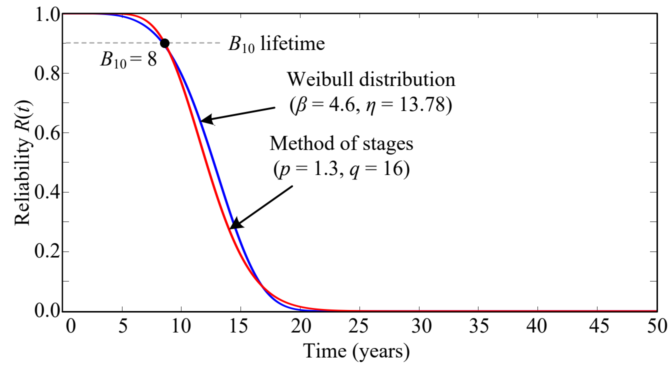

Fig. 6. Reliability of component using Weibull distribution and method of stages (i.e., Special Erlangian distribution).

first and second moments of the Special Erlangian distribution, i.e., m_1 and m_2, can be obtained as

$$m_1 = \frac{q}{p}, \quad m_2 = \frac{q(q+1)}{p^2}$$

while the first two moments of the Weibull distribution, i.e., M_1 and M_2, can be obtained from (4) as:

$$M_1 = \eta\Gamma\Big(\frac{\beta+1}{\beta}\Big), \quad M_2 = \eta^2\Gamma\Big(\frac{\beta+2}{\beta}\Big)$$

By solving $m_1 = M_1$ and $m_2 = M_2$, the number of states in the series combination q and the (constant) failure rate of each state p can be identified as

$$q = \frac{M_1}{M_2 - M_1^2}, \quad p = \frac{M_1^2}{M_2 - M_1^2} \tag{7}$$

where it should be noted that the number of states q may need to be rounded to the nearest integer number.

An example of the method of stages approach is shown in Fig. 6, where the failure rate with Weibull distribution (β = 4.6, η = 13.78) is represented by a series combination of states with exponential distribution following (7). In this case, the total number of q = 16 stages is required and the (constant) failure rate of each state is p = 1.3. As it can be seen from Fig. 6, the two distributions are well aligned and the reliability metric such as B_{10} lifetime (i.e., the time when 10 % failure occurs) of the two distribution is also equal.

C. Markov Chain Model for Wear-Out Failure

The MC model of the FT power converter in Fig. 4, which includes the wear-out failure, is illustrated in Fig. 7(a). Noted that the failure rate during pre-fault $\lambda_{\text{pre}}(t)$ and post-fault $\lambda_{\text{post}}(t)$ are Weibull distribution. The method of stages can be applied to the MC model of the FT power converter by substituting the state with Weibull distribution with a series combination of states with exponential distribution, as illustrated in Fig. 7(b). Then, the state equations of the MC model can be constructed and solved in a similar way as it has been demonstrated in (2). However, it should be noted that the dimension of the transition rates matrix in the state equations now becomes $(q_1+q_2+1)\times(q_1+q_2+1)$ instead of 3×3 as in (2). By solving the state equations, the reliability of the FT power converter can be determined by taken into account all the states that corresponds to the operation (e.g., normal and FT operations) of the power converter as

$$R(t) = \sum_{i=1}^{q_1} P_{1,\text{i}}(t) + \sum_{j=2}^{q_2} P_{2,\text{j}}(t) = 1 - P_3(t) \tag{8}$$

where $P_{1,\text{i}}(t)$ is the probability of being in the i^{th} state of the pre-fault operation while $P_{2,\text{j}}(t)$ is the probability of being in the j^{th} state of the post-fault operation.

IV. Case Study

In this section, the proposed reliability analysis method for FT power converter which includes the wear-out failure will be demonstrated, where a case study of FT power converter in Fig. 4 is considered and applied to PV applications.

A. Mission Profile

The hardware prototype of the PV inverter test-bench is shown in Fig. 8, where the system parameters are provided in Table I. A custom-made printed circuit board (PCB) of the hardware prototype makes it possible to experimentally measure the junction temperature of the power device during operation with an optical fiber. Therefore, the thermal stress profile under mission profile operation can be extracted. From the results in Fig. 9(a), there is good agreement between the thermal stress seen in the experiment and the simulation, which validates the accuracy of the thermal model. Then, Monte Carlo simulations are applied to the thermal model by introducing parameter variation [20], e.g., from component's tolerance, as it is shown in Fig. 9(b). The same process can be applied during both pre-fault and post-fault operations to obtain the distribution of the failure rate during each stage.

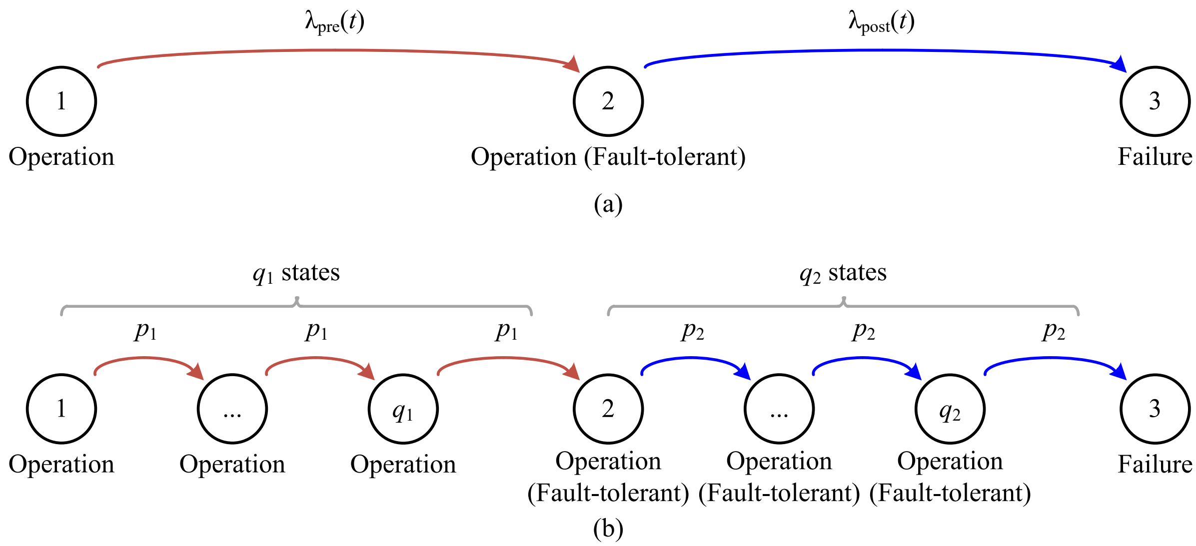

Fig. 7. Markov Chain model of fault-tolerant power converter represented by: a) Weibull distribution where $\lambda_{pre}(t)$ and $\lambda_{post}(t)$ are the failure rates during pre-fault and post-fault operation, respectively, and b) method of stages with q_1 states representing the pre-fault operation with exponential distribution failure rate of p_1 and q_2 states representing the post-fault operation with an exponential distribution failure rate of p_2.

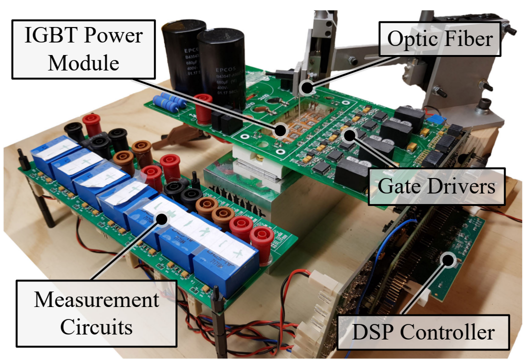

Fig. 8. Hardware prototype of PV inverter with thermal stress measurement.

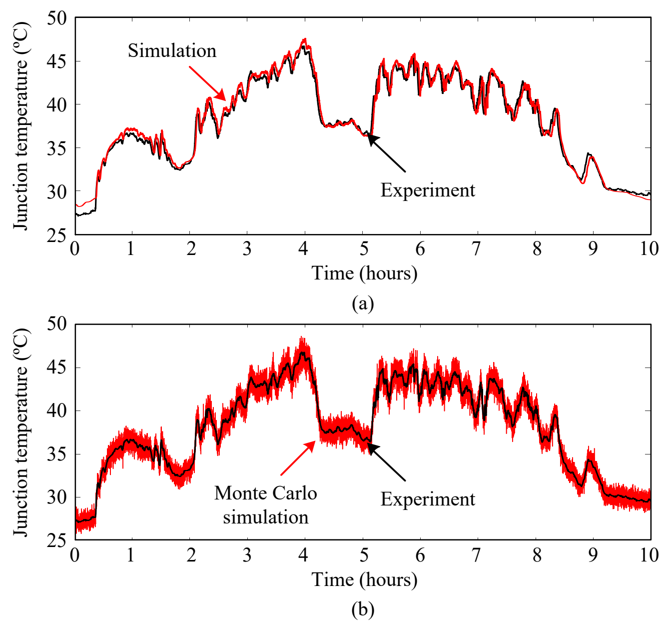

Fig. 9. Experimental and simulation results of one-day thermal stress profile of the PV inverter based on: a) thermal model and b) Monte Carlo simulation.

B. Pre-Fault and Post-Fault Failure Rates

The lifetime (failure) distribution of the power device during pre-fault and post-fault operation of the FT power converter in Fig. 3(b) are shown in Fig. 10. It can be noticed from the results that the failure rate during the post-fault operation is much higher (shorter lifetime) than that during the pre-fault operation. This is mainly because the degradation due to the wear-out that has occurred during the pre-fault operation is taken into account as the initial damage during the post-fault operation [21]. In that case, the power devices will reach their end-of-life relatively faster during post-fault operation compared to the case during the pre-fault condition (even under the same mission profile). The lifetime distribution in Fig. 10 also represents the failure density function, which can be fitted with Weibull distribution with the parameters of $\beta = 4.6$ and $\eta = 13.78$ for the pre-fault operation and $\beta = 1.6$ and $\eta = 2.84$ for the post-fault operation, respectively.

TABLE I
PARAMETERS OF THE PV INVERTER TEST-BENCH.

PV array rated power	10 kW
AC output current (rated)	30 A
DC-link voltage	690 V
DC-link capacitance	C_{dc} = 340 μF
Filter inductance	2.5 mH
Switching frequency	f_{sw} = 10 kHz
Nominal output frequency	f_g = 50 Hz

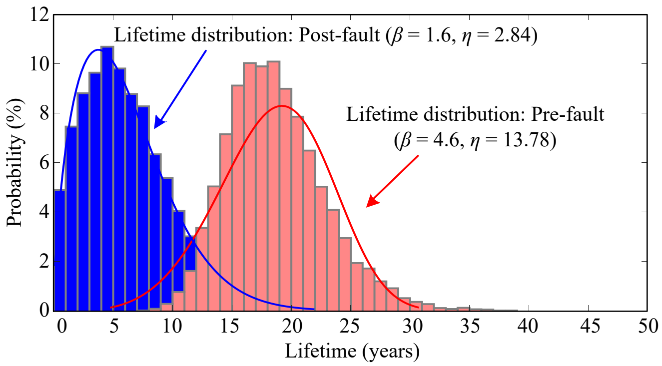

Fig. 10. Lifetime distribution of the FT power converter during pre-fault and post-fault operation.

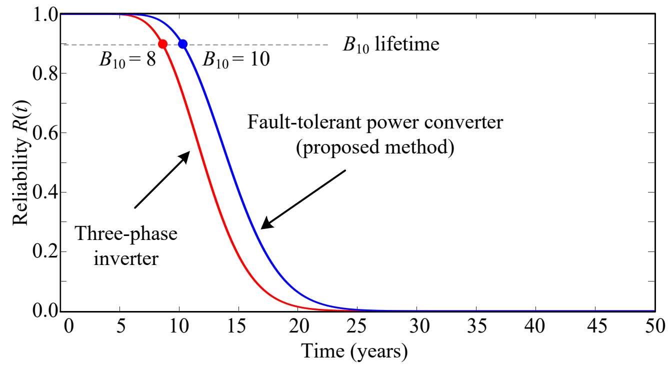

Fig. 11. Reliability comparison between the three-phase inverter and fault-tolerant inverter including wear-out failure using the proposed method.

TABLE II
PARAMETERS OF THE METHOD OF STAGES APPLIED TO THE CASE STUDY.

System Configuration	Weibull Distribution		Special Erlangian	
	β	η	p	q
Pre-fault operation	4.6	13.78	1.30	16
Post-fault operation	1.6	2.84	0.95	2

C. Reliability Analysis

From the failure density function based on Weibull distribution during pre-fault and post-fault operation in Fig. 10, the MC model of the FT power converter can be constructed as it is illustrated in Fig. 7(a). Then, the method of stage can be applied to convert the states with Weibull distribution into an equivalent series combination of states with exponential distribution following Fig. 7(b). The failure rate during pre-fault and post-fault operation in Fig. 10 (which are Weibull distributions) can be applied to the method of stages. In this case, a series combination of q_1 = 16 exponential states with a failure rate of p_1 = 1.30 and q_2 = 2 exponential states with a failure rate of p_2 = 0.95 are required to represent the failure rate during the pre-fault and post-fault operation, respectively, as it is summarized in Table II. Then, the reliability of the FT power converter can be determined from the MC model shown in Fig. 7(b) where the transition rates matrix in (8) has a dimension of $(q_1 + q_2 + 1) \times (q_1 + q_2 + 1) = 19 \times 19$. By solving the state equations, the reliability of the FT power converter can be obtained as it is shown in Fig. 11. It can be seen that the reliability improvement in terms of B_{10} lifetime is 2 years, which is about 25 % compared to the reliability of the three-phase inverter without FT capability.

V. CONCLUSION

The conventional reliability analysis method for FT power converters, which is based on a Markov Chain model, in no longer applicable when the wear-out failure is considered, since the failure rates will not be constant. To solve this issue, this paper proposed a new method to evaluate the reliability of the FT power converter, which can incorporate the wear-out failure into the analysis. The proposed method employs the method of stages to translate a non-constant failure rate into an equivalent multi-state constant failure rate in the MC model. By doing so, the failure rate during both pre-fault and post-fault conditions based on Weibull distribution can be included in the reliability analysis. The proposed method has been demonstrated with a case study of PV inverter having a FT topology, where the reliability improvement can be evaluated.

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REFERENCES

[1] Y. Song and B. Wang, “Survey on reliability of power electronic systems,” *IEEE Trans. Power Electron.*, vol. 28, no. 1, pp. 591–604, Jan. 2013.

[2] R. N. Argile, B. C. Meerow, D. J. Atkinson, A. G. Jack, and P. Sangha, “Reliability analysis of fault tolerant drive topologies,” in *Proc. 4th IET Conf. PEMD*, pp. 11–15, 2008.

[3] Y. Song and B. Wang, “Analysis and experimental verification of a fault-tolerant HEV powertrain,” *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5854–5864, 2013.

[4] W. Zhang, D. Xu, P. N. Enjeti, H. Li, J. T. Hawke, and H. S. Krishnamoorthy, “Survey on fault-tolerant techniques for power electronic converters,” *IEEE Trans. Power Electron.*, vol. 29, no. 12, pp. 6319–6331, 2014.

[5] B. Mirafzal, “Survey of fault-tolerance techniques for three-phase voltage source inverters,” *IEEE Trans. Ind. Electron.*, vol. 61, no. 10, pp. 5192–5202, 2014.

[6] B. A. Welchko, T. A. Lipo, T. M. Jahns, and S. E. Schulz, “Fault tolerant three-phase AC motor drive topologies: a comparison of features, cost, and limitations,” *IEEE Trans. Power Electron.*, vol. 19, no. 4, pp. 1108–1116, 2004.

[7] U.S. Department of Defense, “Reliability prediction of electronic equipment,” Tech. Rep. MIL-HDBK-217F/2, 1991.

[8] P. O’Connor and A. Kleyner, *Practical Reliability Engineering*. John Wiley & Sons, 2012.

[9] H. Wang, M. Liserre, and F. Blaabjerg, “Toward reliable power electronics: Challenges, design tools, and opportunities,” *IEEE Ind. Electron. Mag.*, vol. 7, no. 2, pp. 17–26, 2013.

[10] H. Wang, M. Liserre, F. Blaabjerg, P. de Place Rimmen, J. B. Jacobsen, T. Kvisgaard, and J. Landkildehus, “Transitioning to physics-of-failure as a reliability driver in power electronics,” *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 1, pp. 97–114, 2014.

[11] K. Ma, H. Wang, and F. Blaabjerg, “New approaches to reliability assessment: Using physics-of-failure for prediction and design in power electronics systems,” *IEEE Power Electron. Mag.*, vol. 3, no. 4, pp. 28–41, Dec 2016.
[12] R. Billinton and R. N. Allan, *Reliability evaluation of engineering systems*. Springer, 1992.
[13] E. De Francesco, R. De Francesco, and E. Petritoli, “Obsolescence of the MIL-HDBK-217: A critical review,” in *Proc. of MetroAeroSpace*, pp. 282–286, 2017.
[14] T. H. Liu, J. R. Fu, and T. A. Lipo, “A strategy for improving reliability of field-oriented controlled induction motor drives,” *IEEE Trans. Ind. App.*, vol. 29, no. 5, pp. 910–918, 1993.
[15] J. R. Fu and T. A. Lipo, “A strategy to isolate the switching device fault of a current regulated motor drive,” in *Conf. Rec. IEEE IAS Annu. Meeting*, vol. 2, pp. 1015–1020, 1993.
[16] S. Bolognani, M. Zordan, and M. Zigliotto, “Experimental fault-tolerant control of a PMSM drive,” *IEEE Trans. Ind. Electron.*, vol. 47, no. 5, pp. 1134–1141, 2000.
[17] R. L. de Araujo Ribeiro, C. B. Jacobina, E. R. C. da Silva, and A. M. N. Lima, “Fault-tolerant voltage-fed PWM inverter AC motor drive systems,” *IEEE Trans. Ind. Electron.*, vol. 51, no. 2, pp. 439–446, 2004.
[18] ZVEI, “How to measure lifetime for robustnesss validation - step by step,” Rev. 1.9, Nov. 2012.
[19] C. Singh and R. Billinton, *System Reliability, Modelling and Evaluation*. Hutchinson London, 1977, vol. 769.
[20] M. Novak, A. Sangwongwanich, and F. Blaabjerg, “Monte carlo-based reliability estimation methods for power devices in power electronics systems,” *IEEE Open J. Power Electron*, vol. 2, pp. 523–534, 2021.
[21] A. Sangwongwanich and F. Blaabjerg, “Monte carlo simulation with incremental damage for reliability assessment of power electronics,” *IEEE Trans. Power Electron.*, vol. 36, no. 7, pp. 7366–7371, 2021.