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Improved Markov Model for Reliability Assessment of Isolated Multiple-Switch PWM DC-DC Converters

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ABSTRACT This paper proposes a comprehensive Markov model to study the reliability performance of the conventional isolated multiple-switch pulse width modulation DC-DC (IMSDC-DC) converters including full-bridge, half-bridge and push-pull DC-DC topologies. The suggested model helps to achieve more precise outcomes with a better reflection of the real-world operation characteristics by (i) relying on self-embedded fault tolerant capability of the IMSDC-DC converters, (ii) considering the probability of both short and open circuit (SC and OC) faults in each component, (iii) assessing the effect of semiconductors' SC/OC probability on the converters' reliability, (iv) analyzing the continuous and discontinuous conduction modes, (v) updating the operational characteristics of the converters after each fault occurrence, and (vi) evaluating control of the converters to have more durable power transfer in some post-fault cases. Then, the model is applied to assess the effects of duty cycle, output power, voltage gain and transformer turns ratio on the overall reliability and mean time to failure. Practical analytic conclusions are followed by some experimental results to verify the accuracy of the proposed model.

INDEX TERMS Isolated multiple-switch pulse width modulation DC-DC (IMSDC-DC) converters, Markov model, mean time to failure (MTTF), open and short circuit faults, reliability analytics.

I. INTRODUCTION

Markov models are widely utilized as a solution approach for probabilistic problems in general [1], [2] and reliability evaluation of power electronic converters in particular [3]–[5]. Among various Markov model solution approaches such as Markov process, semi-Markov process and regenerative Markov process, the two last ones are more general and appropriate for complicated large-scale systems [6,7]. Therefore, Markov process has been commonly utilized to solve power electronic-related Markov models with special focusing on DC-DC power converters in recent years. In [8], a Markov model is suggested to analyze the effects of soft switching and interleaving on the reliability performance of a DC-DC converter, where combination of both these techniques results in the best reliability outcome. In [9], some Markov models are employed with the main emphasis on the role of capacitor characteristics to co-optimize the capacitor voltage ripples and converter reliability for a multi-phase DC-DC converter. Reliability-driven operation analytics of a conventional buck-boost converter is discussed in [10], where the effects of input voltage, output power and duty cycle are assessed through a two-state Markov model. In [11], two Markov models are used to simulate the reliability of a single- and a two-stage conventional boost converter with the main aim to evaluate the converter under full or half power in post-fault operation. Some Markov models are applied in [12] and [13] to investigate the reliability performance of a fuel cell power plant including its power conditioning system in which healthy operation, derated and fully faulted states are taken into account. In [14], the impacts of switch and capacitor series resistances on the operation point of other components and overall reliability degradation of a boost converter are analyzed through the obtained results of using a Markov model. Based on the results of [14], the higher the series modeled resistance, the lower the converter's reliability and mean time to failure (MTTF). In [15] and [16], reliability and MTTF are calculated for a multi-level

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topology by using some multi-stage Markov models. An optimized Markov model is further applied on a four-leg matrix converter in [17] to co-optimize the output voltage quality, switching count and electro-magnetic interference. In [18], different operation states are considered in a Markov model to design a grid-connected battery energy storage system. In [19], reliability and MTTF of a soft switching high step-up push pull DC-DC converter is evaluated when faults occur. The main aim of [19] is to analyze the effect of different faults on the converter operation, considering the probability and mechanism of fault tolerance via a Markov model. With special focusing on non-constant failure rates and corrective maintenance factors, a Markov model is suggested in [20] to evaluate the reliability level in a combination of power electronic converters within a larger power system. In [21], some Markov models are utilized to evaluate reliability and MTTF metrics of a multiple-battery storage system in a micro-grid. In [22,23], reliability of the power conditioning systems in a switched reluctance machine is analyzed by considering some Markov models to obtain the optimal control parameters. In [24], [25], reliability of the conventional isolated and non-isolated DC-DC converters is assessed to achieve optimal operational points; however, the rates of components' open and short circuit faults are considered as constants. As one of the important applications of the Markov model approach, the optimized number of interleaved stages is assessed in a fault tolerant boost converter [26]–[28].

According to the literature review, interleaving and adding some extra power electronic or complicated controlling components are the main approaches to achieve better fault tolerance capability. However, by selection of the isolated multiple-switch pulse width modulation DC-DC (IMSDC-DC) converters as the main case study and a meticulous operation analysis, a self-embedded fault tolerant capability is proposed in this paper with no external components, which results in an improved Markov model. The proposed holistic model simulates the reliability performance of the IMSDC-DC converters more precisely by taking the probabilities of short and open circuit (SC and OC) faults of the components into account. The model is applied for both continuous and discontinuous conduction modes (CCM and DCM) to evaluate the effects of (i) SC/OC probability of components, and (ii) duty cycle (D), output power (P_o), transformer turns ratio (n) and voltage gain (G) on the reliability and MTTF of the IMSDC-DC converters.

The rest of this paper is arranged as follows. Detailed operation principles of the IMSDC-DC converters are discussed in Section II. Section III is devoted to the proposed Markov model. Section IV presents the reliability assessment results of the proposed model followed by experimental verification in Section V. Eventually, Section VI concludes the paper.

II. OPERATION PRINCIPLES

In order to elaborate the principles of the self-embedded fault tolerance in the IMSDC-DC converters, the topologies of full-bridge (FB), half-bridge (HB) and push-pull (PP) converters are shown in Fig. 1, in which L_m and L_{Lk} are the magnetizing and leakage inductances of the transformer with $n : 1$ turns ratio, respectively. The aforementioned converters operate in a full power (healthy) state when all components are healthy. However, the converters encounter an absorbing (total failure) state when (i) SC fault of each component, (ii) OC faults of one leg components e.g., D_1-D_2, or (iii) OC faults of complementary switches and/or diodes e.g., S_1-S_3 or S_1-D_3 of the FB converter occur. Meanwhile, the IMSDC-DC converters can tolerate OC faults of some components and continue power transfer to the output load in a derated operation with decreased output power. This introduced operation scenario mimics the flyback converter operation strategy with unipolar transformer core utilization, which was primarily driven by bipolar operation in the healthy state. As an example in Fig. 1(b), half of the HB converter switching cycle is useless with an OC fault of the S_1 switch, while the converter can continue its operation in the next half with the S_2 switch operation through a simple control similar to the flyback converter. In this state, L_m is primarily charged through C_1 and S_2 with $V_i/2$, which is discharged to the output load through D_2 and D_3 in the S_2 turn-off interval (note the current flow path in Fig. 1(b)). Since the proposed fault tolerant strategy is applied without any external power electronic or control components, it is nominated as a self-embedded fault tolerance, which is satisfied under OC faults of (i) one switch or diode, and (ii) corresponding switches and/or diodes e.g., S_1-S_4, D_1-D_4, or S_1-D_1.

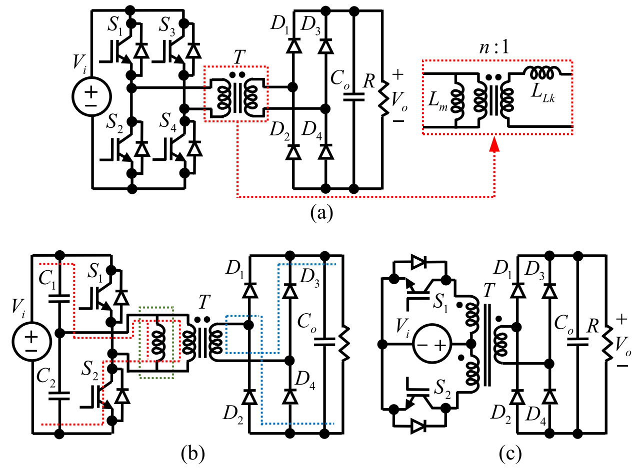


FIGURE 1. Isolated multiple-switch DC-DC converters: (a) Full-bridge (b) Half-bridge (c) Push-pull.

III. METHODOLOGY: THE PROPOSED MARKOV MODEL

According to the explained corresponding probable operation state of each SC or OC fault scenario, the proposed Markov models of the IMSDC-DC converters are illustrated in Fig. 2, where four, five and four states are allocated for FB, HB and PP converters, respectively. The first and the last states reflect the healthy and absorbing states, and the other intermediate ones indicate the derated states. In Fig. 2, $\lambda_{ij}(i \neq j)$ is the failure rate of the converter from state i to j, which is also

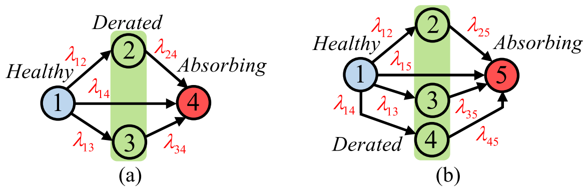


FIGURE 2. Proposed Markov models. (a) Full-bridge and push-pull. (b) Half-bridge.

TABLE 1. Transition failure rates of the isolated multiple-switch DC-DC converters.

Converter	Failure rate	Equation
FB	λ_{12}	$4(1-\alpha_S)\lambda_S$
	λ_{13}	$4(1-\alpha_D)\lambda_D$
	λ_{14}	$\lambda_T+\lambda_{Co}+4\alpha_S\lambda_S+4\alpha_D\lambda_D$
	λ_{24}	$\lambda_T+\lambda_{Co}+(2+\alpha_S)\lambda_S+(2+2\alpha_D)\lambda_D$
	λ_{34}	$\lambda_T+\lambda_{Co}+(2+2\alpha_S)\lambda_S+(2+\alpha_D)\lambda_D$
HB	λ_{12}	$2(1-\alpha_S)\lambda_S$
	λ_{13}	$2\lambda_C$
	λ_{14}	$4(1-\alpha_D)\lambda_D$
	λ_{15}	$\lambda_T+\lambda_{Co}+2\alpha_S\lambda_S+4\alpha_D\lambda_D$
	λ_{25}	$\lambda_T+\lambda_{Co}+\lambda_C+\lambda_S+(2+2\alpha_D)\lambda_D$
	λ_{35}	$\lambda_T+\lambda_{Co}+\lambda_C+\lambda_S+(2+2\alpha_D)\lambda_D$
	λ_{45}	$\lambda_T+\lambda_{Co}+\lambda_C+(1+\alpha_S)\lambda_S+(2+\alpha_D)\lambda_D$
PP	λ_{12}	$2(1-\alpha_S)\lambda_S$
	λ_{13}	$4(1-\alpha_D)\lambda_D$
	λ_{14}	$\lambda_T+\lambda_{Co}+2\alpha_S\lambda_S+4\alpha_D\lambda_D$
	λ_{24}	$\lambda_T+\lambda_{Co}+\lambda_S+(2+2\alpha_D)\lambda_D$
	λ_{34}	$\lambda_T+\lambda_{Co}+(1+\alpha_S)\lambda_S+(2+\alpha_D)\lambda_D$

defined in Table 1. In this table, λ_T, λ_S, λ_D, λ_C, λ_{Co} are the failure rates of the transformer, switch, diode, input blocking and output capacitors, respectively, which are derived from the power loss calculations of [29] and the formulated failure rate equations of the MIL-HDBK-217 [30,31]. In addition, as a significant contribution of this paper, the probabilities of OC and SC fault scenarios in each semiconductor component are assumed as variables of α_S (SC probability of S) and α_D (SC probability of D), where $\alpha_S, \alpha_D > 0.5$ [32]. Accordingly, the OC probabilities of S and D are equal to $1-\alpha_S$ and $1-\alpha_D$, respectively. Furthermore, only the SC fault is considered for passive components, reflecting their practical fault characteristics. In order to clarify the calculated λ_{ij} in Table 1, λ_{34} of the FB converter is obtained as follows:

$$\lambda_{34} = \lambda_T + \lambda_{Co} + 2(1-\alpha_S)\lambda_S + 4\alpha_S\lambda_S + 2(1-\alpha_D)\lambda_D + 3\alpha_D\lambda_D \quad (1)$$

where, each of the summation elements represents a SC or OC fault in one component and the numerical coefficients reflect the number of involved components to the failure risk.

Considering the proposed model, reliability of the IMSDC-DC converter is equal to

$$R(t) = \sum_{i=1}^{K} P_i(t) \quad (2)$$

where, $P_i(t)$ and K are the occurrence probability of state i and the number of healthy and derated states (the states with power transfer capability), respectively. In addition, $P_i(t)$ is calculated through the following differential matrix equation.

$$\begin{aligned} {}^{d}/_{dt}\left[P_1(t)\cdots P_{K+1}(t)\right] &= \left[P_1(t)\cdots P_{K+1}(t)\right] \\ &\times \begin{bmatrix} \lambda_{11} & \ldots & \lambda_{1K} & \lambda_{1(K+1)} \\ 0 & \ddots & 0 & \vdots \\ 0 & 0 & \lambda_{KK} & \lambda_{K(K+1)} \\ 0 & 0 & 0 & 0 \end{bmatrix}_{(K+1)\times(K+1)} \end{aligned} \quad (3)$$

By assuming the healthy state as the initial analysis state, which leads to $\left[P_1(0)\ P_2(0)\cdots P_{K+1}(0)\right] = \left[1\ 0\cdots 0\right]$, $P_i(t)$ is defined as

$$P_i(t) = \begin{cases} e^{\lambda_{ii}t} & ;\ i=1 \\ \dfrac{\lambda_{1i}}{\lambda_{11}-\lambda_{ii}}\left(e^{\lambda_{11}t}-e^{\lambda_{ii}t}\right) & ;\ i\neq 1 \end{cases} \quad (4)$$

Then, MTTF is obtained as

$$\begin{aligned} MTTF &= \int_{t=0}^{\infty} R(t)dt \\ &= \frac{-1}{\lambda_{11}} + \sum_{i=2}^{K} \frac{\lambda_{1i}}{\lambda_{11}-\lambda_{ii}}\left(\frac{1}{\lambda_{ii}} - \frac{1}{\lambda_{11}}\right) \end{aligned} \quad (5)$$

IV. PROPOSED MODEL IMPLEMENTATION: RELIABILITY ASSESSMENT RESULTS

In this study, the IMSDC-DC converters' components are designed according to [29] with $L_m = 5\,mH$, $L_{Lk} = 500\,\mu H$, $C_1 = C_2 = C_o = 33\,\mu F$ and $R = 100\,\Omega$, which lead to the boundary duty cycle of $D_B = 0.3$. Two sample semiconductors with forward voltage drop and ON resistance of $1\,V$-$0.049\,\Omega$ and $1.5\,V$-$0.023\,\Omega$ are assumed as the switch and diode, respectively. In addition, passive components are considered non-ideal, and minimum and maximum acceptable duty cycles are $D_{\min} = 0.1$ and $D_{\max} = 0.5$, respectively. The values of $\alpha_S = \alpha_D = 0.8$, $P_o = 100\,W$, $f_S = 20\,kHz$(switching frequency), $n = 1$, $t = 0.4 \times 10^6$ Hours (operation time duration), $D_{DCM} = 1/6$ and $D_{CCM} = 1/3$ are initially assumed, which are considered as variables of the test scenarios when evaluating their own impacts on the overall reliability of the converters. The reliability assessment results are expressed in Figs. 3-6 with the main aim of analyzing the effects of α_S, α_D, D, P_o, n, G and t, where the following general and practical issues are concluded:

- P_o has an inverse relation with reliability; however, an optimal point is found in the converters' reliability with respect to D, n and G (Figs. 3(a), 4(a), 5(a) and 6(a)),

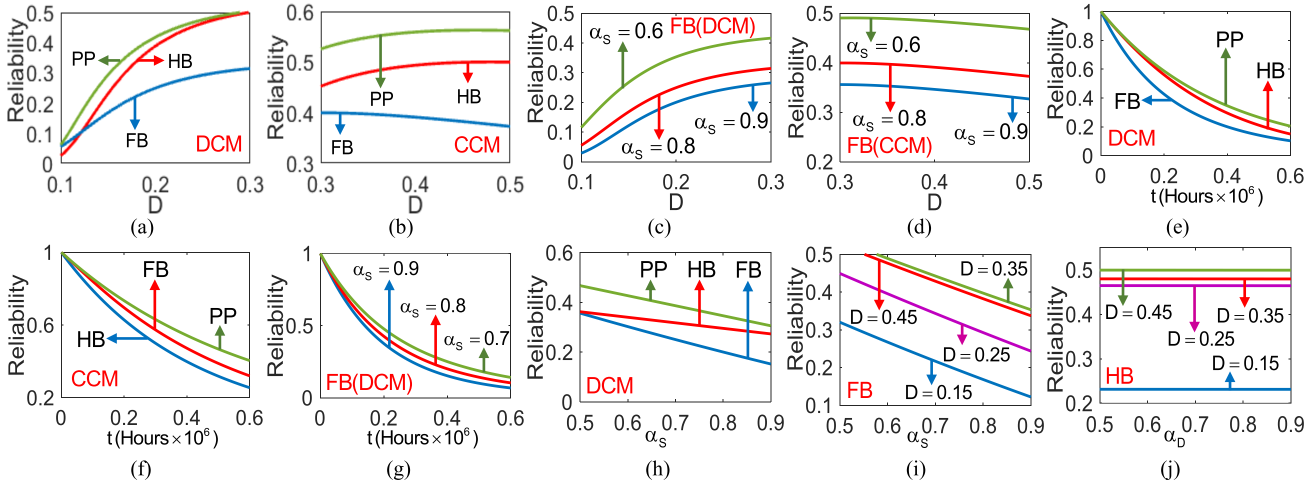


FIGURE 3. Reliability performance of IMSDC-DC converters according to the proposed Markov model to evaluate the effects of D, t, α_S and α_D.

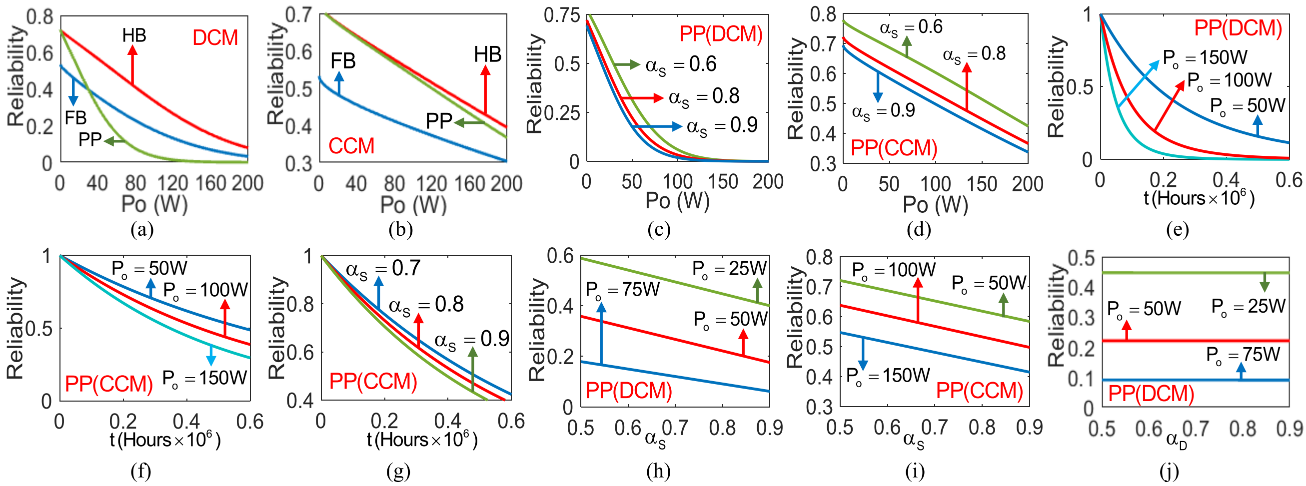


FIGURE 4. Reliability performance of IMSDC-DC converters according to the proposed Markov model to evaluate the effects of P_o, t, α_S and α_D.

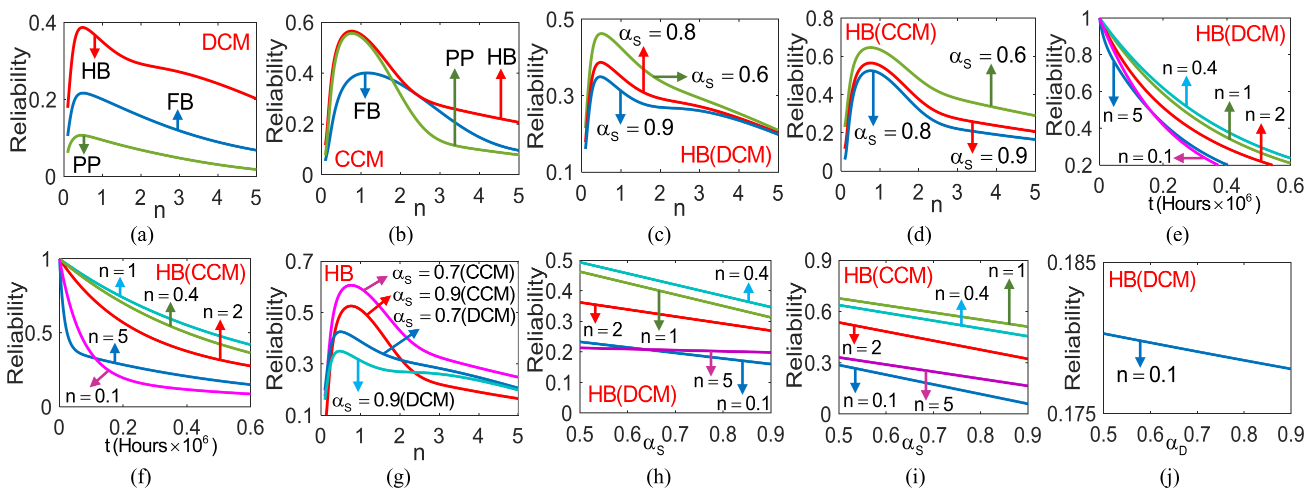


FIGURE 5. Reliability performance of IMSDC-DC converters according to the proposed Markov model to evaluate the effects of n, t, α_S and α_D.

- Lower α_S of the utilized switch leads to more reliable converters; however, α_D has an ignorable impact,
- Although behavior of the calculated reliability metric is not linear with respect to the α_S variation, it can be linearized with an acceptable approximation,

- The rate of reliability variation is different in each operation point of the specific converter with respect to α_S changes (Figs. 5(h, i) or Figs. 6(i, j)),
- Characteristically, α_S has similar impact on the IMSDC-DC converters; however with different rates, according to differences in the number and voltage stress of switches among the FB, HB and PP converters,
- The rate of reliability reduction is different in the specific IMSDC-DC converter in its CCM and DCM operation for a certain α_S change,
- Reliability of the CCM operation in the specific IMSDC-DC converter is more sensitive to the α_D variation than its DCM operation,
- Considering D variation, $D_{\min}$ owes the worst reliability metric (Figs. 3(a) and (c)),
- According to the voltage gain relation of the IMSDC-DC converters ($G \propto D/n$), both D and n affect G; however, for a specific G value around "1", designing and operating with higher D and n values is more reliable,
- Due to the use of four switches in the primary side, the FB converter is not a suitable candidate among IMSDC-DC converters from a reliability point of view,
- According to aging mechanism, t has inverse impact on the reliability.

Moreover, the detailed and exclusive results of Fig. 3 with main concentration on the effect of D variation are listed as: (i) Under a constant output load, CCM operation of the IMSDC-DC converters has higher reliability (Figs. 3(a, b)), (ii) The maximum reliability performance is achieved in $D = 0.31$, 0.47 and 0.47 for the designed FB, HB and PP converters, respectively (Figs. 3(a, b)), (iii) Unlike HB and PP, the reliability of the FB converter decreases when D increases in CCM according to its more switches, (iv) Reliability of the HB converter has the lowest sensitivity against α_S changes due to its lowest switch count and voltage stress (Fig. 3(h)), and (v) Reliability of the HB converter owes the highest sensitivity with respect to D variation (Figs. 3(a, b)). Considering Fig. 4, the HB converter has the highest reliability in variable P_o, reliability of the PP converter is the most sensitive with respect to P_o changes (Figs. 4(a, b)), CCM operation is more robust with respect to P_o variation (Figs. 4(c, d)), the rate of reliability reduction with respect to α_S increment is higher in lower P_o values of DCM operation (Fig. 4(h)), and PP converter does not have optimal operation in $P_o > 100W$ and $t > 0.3 \times 10^6 h$ for DCM operation under the assumed design (Fig. 4(e)). In the transformer turns ratio analytics of Fig. 5, the following points are resulted: (i) $0.1 < n < 1$ leads to better reliability performance (Fig. 5(a, b)), (ii) $n < 0.1$ and $n > 5$ are not suitable design cases from reliability point of view, (iii) The corresponding n value of the maximum reliability points decreases by the increment of α_S (Figs. 5(c, d)), (iv) In $\alpha_S = 0.8$, the reliability of the designed FB, HB and PP converters reach to their maximum point at $n = 1.15$, 0.76 and 0.78 for CCM, and 0.50, 0.48 and 0.46 for DCM, respectively (Figs. 5(a, b)), (v) n has the highest impact on CCM

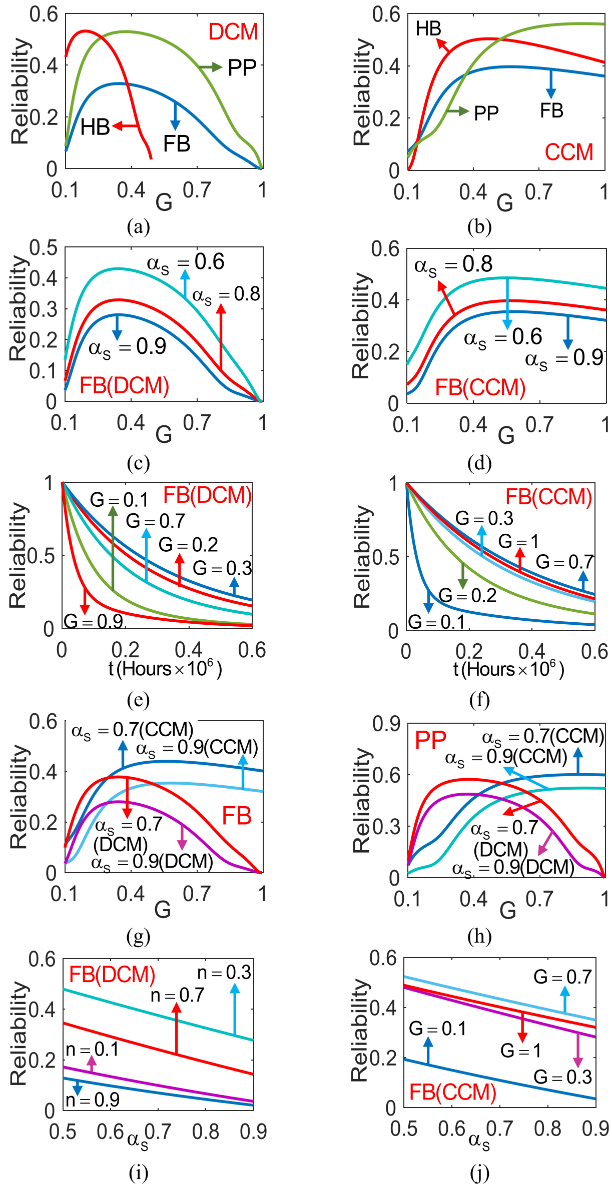


FIGURE 6. Reliability performance of IMSDC-DC converters according to the proposed Markov model to evaluate the effects of G, t, α_S and α_D.

PP based on its one more transformer winding (Fig. 5(b)), and (vi) the rate of reliability reduction with respect to α_S increment is the highest in the corresponding n value of the maximum reliability point (Fig. 4(h)). Eventually, based on the comparative diagrams in Fig. 6, the conclusive hints of the voltage gain results are: (i) From a variable G point of view, DCM and CCM have better reliability performance in low and high G, respectively (Figs. 6(g, h)), (ii) $G = 0.29$, 0.31 and 0.52 are the boundary voltage gain values for the FB, HB and PP, respectively, where each of CCM and DCM operation has higher reliability in their one side, (iii) Increment of α_S leads to a reduction of the corresponding G value of the maximum reliability points, (iv) $G < 0.1$ owes a low reliability value in both DCM and CCM operations with $n = 1$ design; hence, designing with higher n values is necessary to improve the reliability metric in $G < 0.1$,

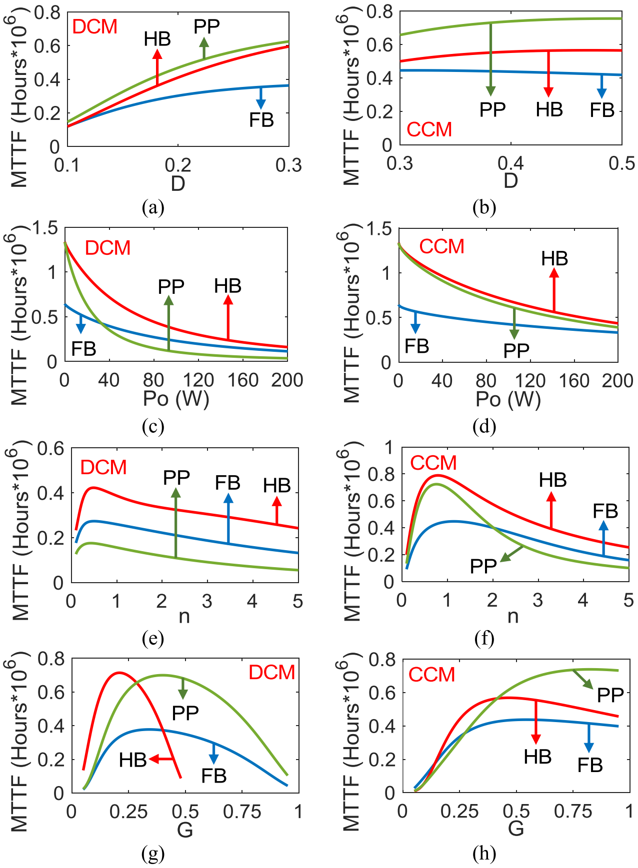


FIGURE 7. MTTF evaluation in DCM and CCM operation with respect to: (a, b) *D*. (c, d) P_O. (e, f) *n*. (g, h) *G*.

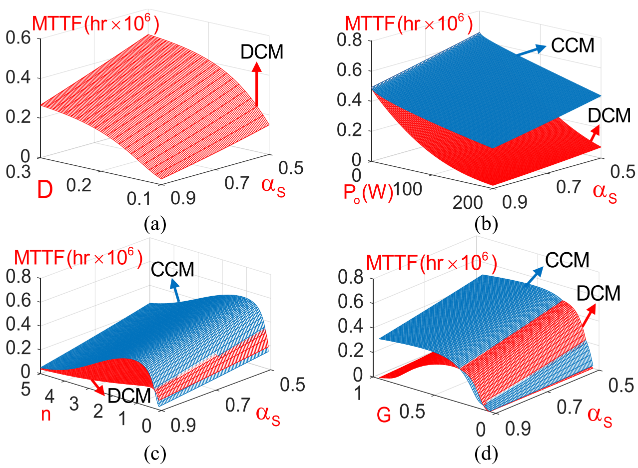


FIGURE 8. Three-dimensional MTTF evaluation of the full-bridge converter with respect to α_s and: (a) *D*. (b) P_O. (c) *n*. (d) *G*.

(v) In $\alpha_S = 0.8$, the maximum reliability points of the designed FB, HB and PP converters occur at $G = 0.57$, 0.47 and 0.9 for CCM, and 0.34, 0.19 and 0.38 for DCM, respectively (Figs. 6(a, b)).

In addition, MTTF of the IMSDC-DC converters is assessed based on (5) and the results are illustrated in Figs. 7 and 8. In Fig. 7, MTTF of the converters is compared under the same operation condition in DCM and CCM, which

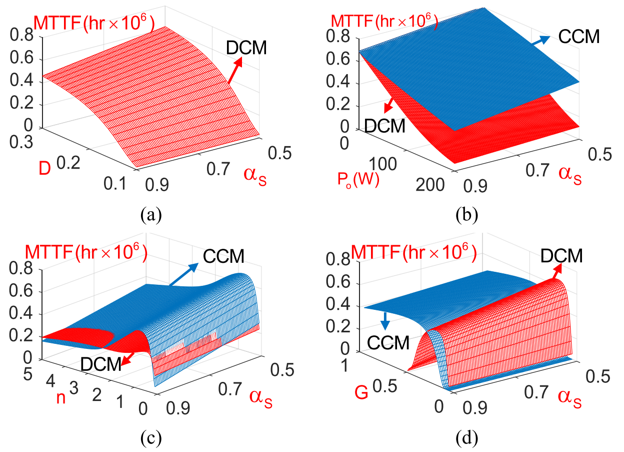


FIGURE 9. Three-dimensional MTTF evaluation of the half-bridge converter with respect to α s and: (a) *D*. (b) P_O. (c) *n*. (d) *G*.

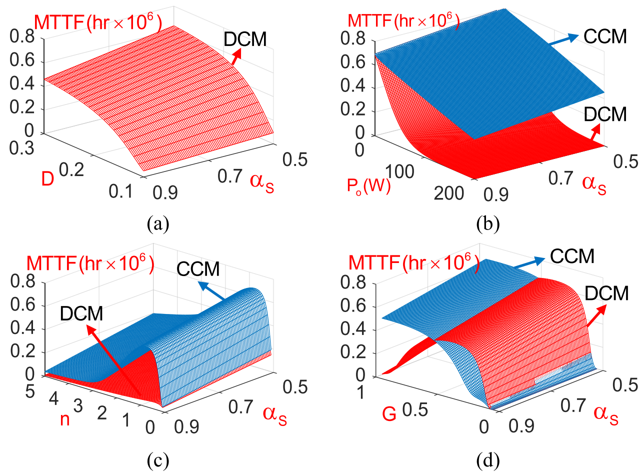
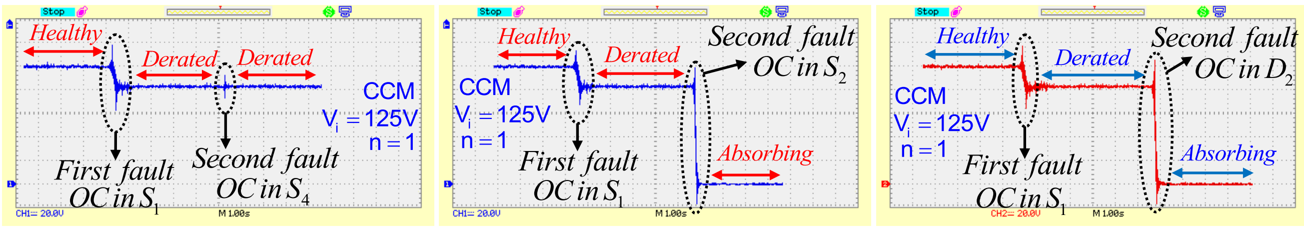


FIGURE 10. Three-dimensional MTTF evaluation of the push-pull converter with respect to as and: (a) *D*. (b) P_O. (c) *n*. (d) *G*.

follows the corresponding reliability performance analytics in Figs. 3-6. Meanwhile, the effect of α_S is presented in three-dimensional diagrams of Figs. 8-10, in which MTTF of FB, HB and PP are depicted with respect to D, P_o, n and G along with α_S. Similar characteristics of reliability and MTTF metrics comes from the independency of t to D, P_o, n and G, where MTTF is the integration of reliability with respect to t.

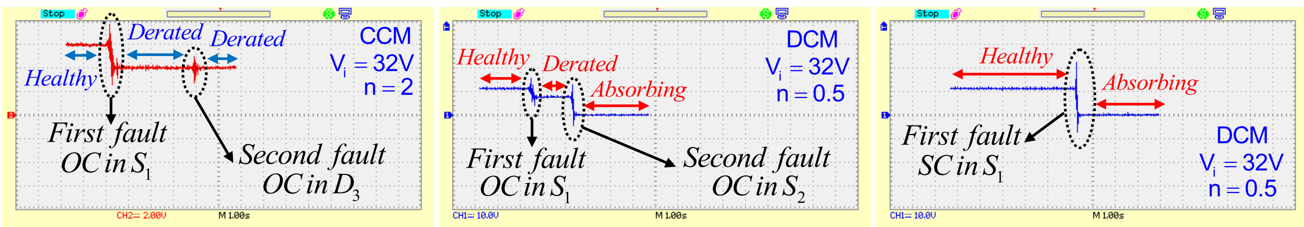
V. EXPERIMENTAL VERIFICATION

In order to validate the self-embedded fault tolerance capability of the proposed Markov model, an experimental FB converter prototype with $V_i = 125\,V$ and $n = 1$ is tested under different OC fault scenarios and the results are shown in Fig. 11. According to this figure, an OC fault in S_1 leads to a derated state, which is presented by State 2 in Fig. 2(a). However, the subsequent OC faults of a corresponding semiconductor (S_4) in Fig. 11(a), and complementary semiconductors (S_2 and D_2) in Figs. 11(b) and (c) result in a derated (State 2 in Fig. 2(a)) and an absorbing state



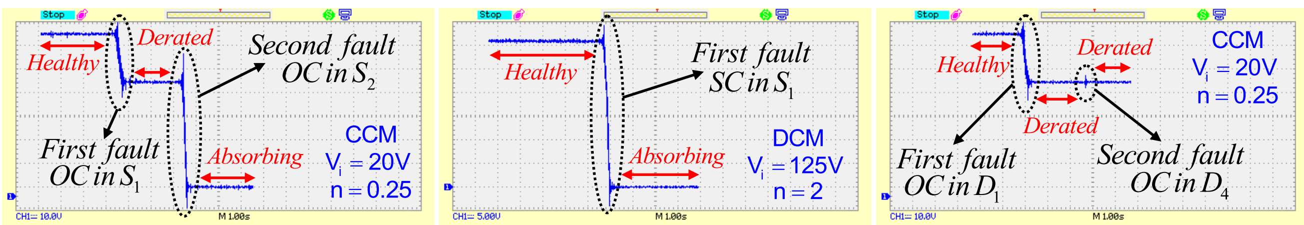
(a) (b) (c)

FIGURE 11. Experimental output voltage changes of the full-bridge converter under different consecutive OC faults of: (a) S_1 and S_4. (b) S_1 and S_2. (c) S_1 and D_2.



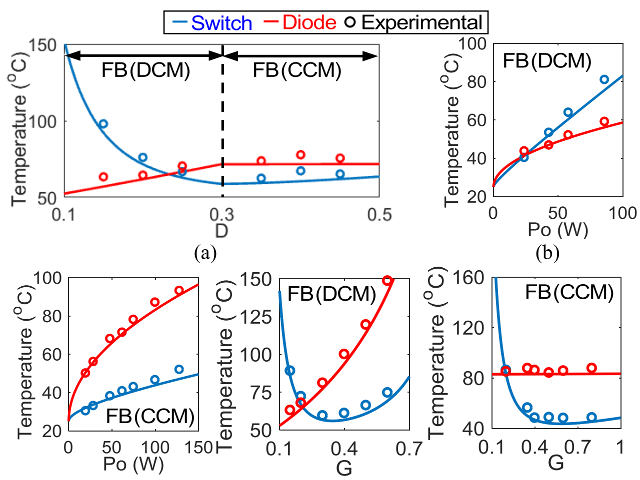
(a) (b) (c)

FIGURE 12. Experimental output voltage changes of the half-bridge converter under different consecutive faults: (a) OC in S_1 and D_3. (b) OC in S_1 and S_2. (c) SC in S_1.



(a) (b) (c)

FIGURE 13. Experimental output voltage changes of the push-pull converter under different consecutive faults: (a) OC in S_1 and S_2. (b) SC in S_1. (c) OC in D_1 and D_4.



(a) (b) (c) (d) (e)

FIGURE 14. Comparison of switch and diode experimental and theoretical thermal tests in the FB converter with respect to: (a) Duty cycle. (b, c) Output power. (d, e) Voltage gain.

(State 4 in Fig. 2(a)), respectively. As demonstrated in Fig. 11, the converter can be controlled to operate in lower output voltage (power) of some derated states and prevent power cut-off. In order to generalize the proposed Markov model, some other OC and SC tests are performed on the HB and PP converters with various *D*, *n*, *G* and input voltage (output power) values in Figs. 12 and 13. The OC tests of the corresponding and complementary semiconductors lead to similar results of Fig. 11. However, the SC tests in Figs. 12(c) and 13(b) results in the absorbing state, which verify the theoretical analysis of Section II. In addition, the fabricated FB converter prototype is tested under thermal experiments and the recorded temperatures are compared with the theoretical analytics in Fig. 14 to validate the accuracy of the calculated failure rates.

VI. CONCLUSION

In this paper, a holistic Markov model was offered to reliability assessment of the IMSDC-DC converters, as one of the mostly used family of DC-DC converters, in order to achieve more dependable results. The proposed model, which can be generalized to the all types of multiple-switch converters, is obtained according to the following steps: (i) analyzing the converter behavior after each SC and OC fault, and defining model states, (ii) applying coefficients of SC and OC probabilities in the model, (iii) calculating power loss of converter components in each state, (iv) determining transition failure rates, and (v) obtaining reliability and MTTF of the converter by utilizing state space equations. The model: (i) includes the effects of both OC and SC faults of components, which results in some derated operation states based on the self-embedded fault tolerance capability of the aforementioned converters, (ii) updates the operational characteristics of the converters after each fault occurrence, (iii) considers the whole probable failure rates of passive and active components, and (iv) ignores the effects of manufacturing-related parameters like soldering and printed circuit board (PCB) design. The OC and SC probabilities of semiconductors are considered as variables to simulate their fault characteristics on the overall reliability of converters. The suggested model is employed to evaluate the effects of duty cycle, output power, transformer turns ratio and voltage gain in both DCM and CCM operations, which is followed by some experimental fault tests to demonstrate the assumptions of operation. According to the reliability analytics, the inverse relation of output power, existence of an optimal point with respect to duty cycle, transformer turns ratio and voltage gain, higher reliability performance of CCM operation, inverse relation of the switch SC probability and an ignorable impact of the diode SC probability are concluded.

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