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Reliability Assessment of Conventional Isolated PWM DC-DC Converters

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ABSTRACT This paper sets forth the reliability analysis of conventional isolated pulse width modulation DC-DC (IDC-DC) converters. The IDC-DC converters are categorized into isolated single-switch DC-DC (ISSDC-DC) or multiple-switch DC-DC (IMSDC-DC) converters. The proposed framework encompasses analyzing the impacts of duty cycle, input voltage, output power, transformer turns ratio, components characteristics and time duration on the overall reliability performance of the IDC-DC converters. The suggested reliability assessment is centered on Markov models characterized by taking into consideration all open and short circuit faults on the components in both continuous and discontinuous conduction modes. We further investigate the self-embedded fault tolerant capability of the IMSDC-DC converters under open circuit fault scenarios on the switches, diodes and blocking capacitors, where we offer new reliability analytics. Along with extensive analyses and comparisons, several experimental results are provided to verify the self-embedded fault tolerant capability of IMSDC-DC converters.

INDEX TERMS Isolated single-switch DC-DC converter (ISSDC-DC), isolated multiple-switch DC-DC converter (IMSDC-DC), fault analysis, Markov process, reliability.

I. INTRODUCTION

Reliability assessment of power electronic converters, if approached meticulously and verified experimentally, can provide insightful information for the system planers and operators. Widespread research efforts have been done in the past years focused on analyzing the reliability performance of power electronic converters [1], [2]. In [3]–[5], reliability principles on the power electronic converters are generally studied with the focus primarily on IGBT modules, redundant structures and industrial applications, respectively. In [6], the effects of components characteristics are assessed on the operating point and reliability performance of a conventional pulse width modulation boost converter to optimize the maintenance costs. In [7], an optimal design of the LC filter in a buck converter is pursued taking into account multiple factors of reliability, power density, cost, voltage and current ripples. In [8], the reliability of a three-phase interleaved boost converter has been improved via soft switching techniques with no auxiliary components. In [9], an optimization model is proposed on an interleaved boost converter seeking a trade-off between the reliability and cost, where the number of interleaved boost converter stages is the optimization degree of freedom. In [10], reliability performances of a single-stage and an interleaved boost converter are compared. With the ability to continue operation in both half and full nominal power modes following a failure in either stage, the two-stage interleaved boost converter with half power operation is attributed to have the highest reliability performance, while realized at the cost of additional number of components compared to a single-stage configuration. In [11], reliability analysis on an isolated DC-DC converter in backup power

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supply application is presented, where it captures the effects of current and voltage stresses, ambient and junction temperatures, conduction and switching losses and load profiles to characterize the converter lifetime.

Mean time to failure (MTTF) of the power electronic converters with fault tolerance capability helps evaluating performance during their useful lifetime. In many converters, the fault tolerance capability is achieved via integration of extra components, software reconfigurations, or interleaving. For instance, the interleaving approach is presented in [1], [8]–[10], while [12], [13] are focused on adding extra auxiliary components or software reconfiguration. A general review of such mechanisms is provided in [14], [15].

In this paper, we provide a comprehensive analysis of the isolated conventional pulse width modulation DC-DC (IDC-DC) converters primarily from a reliability perspective, where the research has been focused on specific component parameters and characteristics. We here evaluate the impacts of different effective operating factors such as duty cycle (D), input voltage (V_i), output power (P_o), transformer turns ratio (n) and component characteristics besides time durations (t) on the overall reliability performance of the IDC-DC converters. Furthermore, short circuit (SC) and open circuit (OC) faults on all converter components are taken into account in the corresponding Markov models of each converter topology in both continuous and discontinuous conduction modes (CCM and DCM). A substantial part of the proposed framework focuses on the self-embedded fault tolerance capability of isolated multiple-switch DC-DC (IMSDC-DC) converters under OC fault scenarios. This capability is clarified through theoretical advancements and experimental verifications, which in turn helps for precise observations and reliable conclusions on the systems.

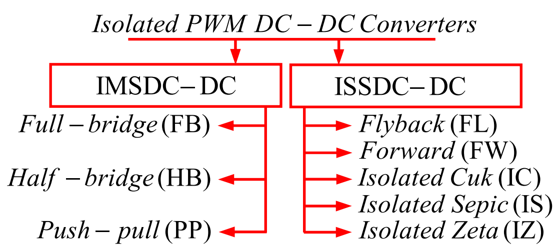

FIGURE 1. Classification of the IDC-DC converters.

II. OPERATIONAL PRINCIPLES

IDC-DC converters are categorized into IMSDC-DC and isolated single-switch DC-DC (ISSDC-DC) converters, where the related items in each category are presented in Fig. 1, with topologies for ISSDC-DC and IMSDC-DC classes of converters illustrated in Fig. 2 and Fig. 3, respectively. As demonstrated in Fig. 3, the non-ideal transformer in the IMSDC-DC converters is modeled by an ideal transformer with turns ratio of n:1, a magnetizing (L_m) and a leakage (L_{LK}) inductance. According to this classification, the ISSDC-DC and IMSDC-DC converter topologies would reveal different responses to various faults in their components.

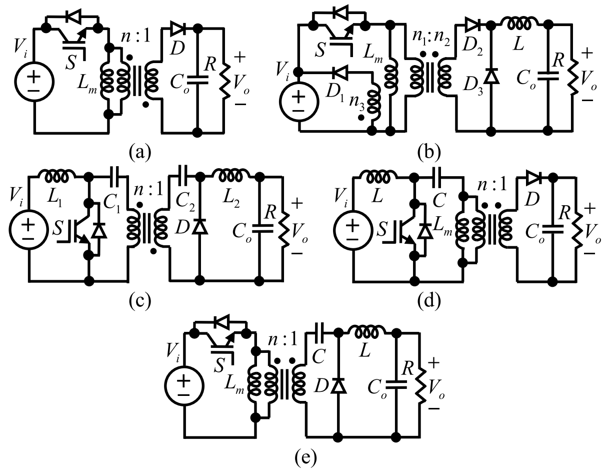

FIGURE 2. ISSDC-DC converters. (a) FL. (b) FW. (c) IC. (d) IS. (e) IZ.

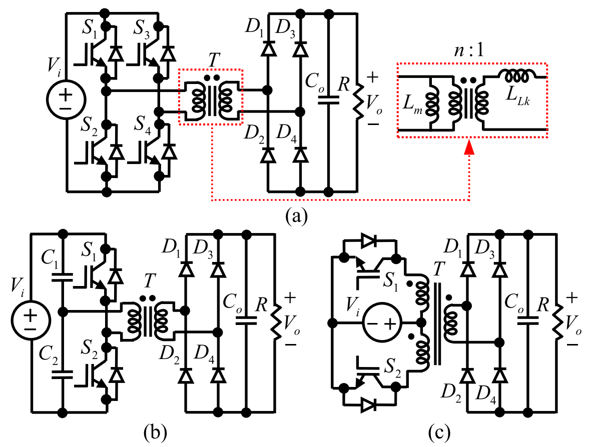

FIGURE 3. IMSDC-DC converters. (a) FB. (b) HB. (c) PP.

In ISSDC-DC converters, the SC or OC faults on each component results in total system failure (i.e., absorbing state). This is valid for the SC faults on the IMSDC-DC converter components as well, while such converters can continue their operation in a derated (partial power) operating states under OC faults in one or several components. These operating states with durable OC faults are listed as follows:

- On one primary (secondary)-side switch (diode) or simultaneously on the corresponding switches (diodes), e.g., S_1 and S_4 switches or D_1 and D_4 diodes,
- On an input blocking capacitor in HB converter,
- Simultaneously on the corresponding switches and diodes from the primary and secondary-sides, e.g., S_1 and D_1 in FB converter.

For instance, if the S_1 switch in Fig. 3(b) faces an OC fault, the HB converter can still continue its operation in a derated power condition similar to the flyback converter. Under such scenarios, half of the converter switching period, which was previously operated by this switch, would not function. However, the HB converter can continue its power transfer to the output load in the other half switching period, operated by the S_2 switch. This operation is similar to that for the flyback converter with an input blocking capacitor and two series secondary-side diodes. Unlike the healthy operating state in HB, L_m stores the magnetic energy and transfers this energy to the output load. Note that the transformer core is designed for the HB bipolar operation and in this state, flyback operation harnesses a unipolar core utilization [16]. The designed core is, however, suitable for the derated power density of the flyback operation [17]. Furthermore, L_{Lk} is negligible in this operation since the HB converter design requires much higher L_m than the L_{Lk}. In this example, the converter's fault tolerance is satisfied without any auxiliary hardware or software components, and thereby confirming its "self-embedded fault tolerance".

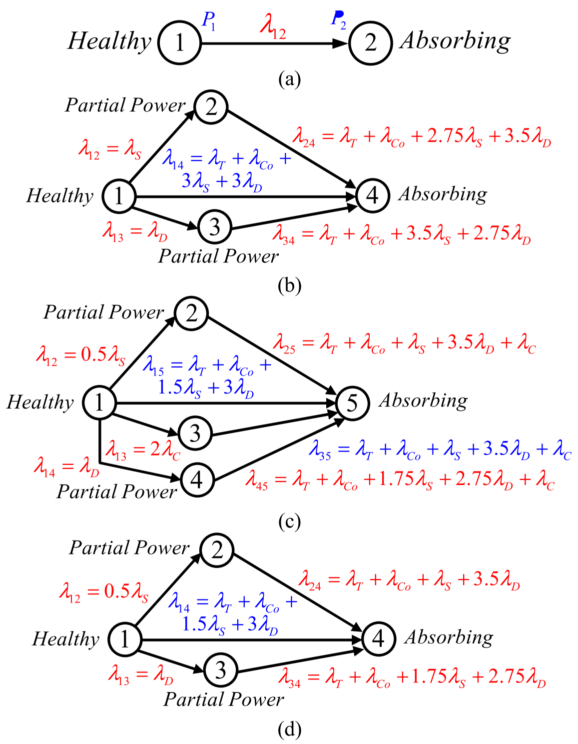

FIGURE 4. Markov models. (a) ISSDC-DC converters. (b) FB. (c) HB. (d) PP.

III. MARKOV MODEL

In this paper, continuous Markov process is utilized to formulate the reliability performance of the IDC-DC converters. Considering the operation principles of these converters against different faults, the corresponding Markov models are illustrated in Fig. 4, where the ISSDC-DC, FB, HB and PP converters are characterized with two, four, five and four operating states, respectively. States 2 and 3 in FB and PP converters, and states 2-4 in HB converter are the derated states. According to [18], [19], reliability performance of systems with two-state Markov model (e.g., the ISSDC-DC converters) can be achieved as follows:

$$R(t) = P_1(t) = e^{-\lambda_{12} t} \tag{1}$$

where, λ_{12} is the summation of components' failure rates under both OC and SC faults. MTTF of these converters is assessed as

$$MTTF = \int_{t=0}^{\infty} P_1(t)\, dt = 1/\lambda_{12} \tag{2}$$

According to the Markov models in Fig. 4(b)-(d), the reliability performance of the IMSDC-DC converters is equal to

$$R(t) = \sum_{i=1}^{s} P_i(t) \tag{3}$$

where, $P_i(t)$ is the probability of operating state i and s is the number of operating states, including both healthy and derated states (= three, four and three for FB, HB and PP converters, respectively). In order to evaluate $P_i(t)$, a state space matrix equation is considered as follows:

$$\begin{aligned} {}^{d}\!/_{dt}\left[P_1(t)\ldots\ P_{s+1}(t)\right] &= \left[P_1(t)\ldots\ P_{s+1}(t)\right] \\ &\quad \times \begin{cases} [A]\,;\ \text{For FB and PP} \\ [B]\,;\ \text{For HB} \end{cases} \end{aligned} \tag{4}$$

where, $[A]$ and $[B]$ are determined as follows:

$$[A] = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} \\ 0 & \lambda_{22} & 0 & \lambda_{24} \\ 0 & 0 & \lambda_{33} & \lambda_{34} \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad [B] = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} & \lambda_{15} \\ 0 & \lambda_{22} & 0 & 0 & \lambda_{25} \\ 0 & 0 & \lambda_{33} & 0 & \lambda_{35} \\ 0 & 0 & 0 & \lambda_{44} & \lambda_{45} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

and, λ_{ij} ($i \neq j$) is the failure rate form operating state i to j, which is presented in Fig. 4(b)-(d). Furthermore, λ_{ii} is defined as the negative summation of failure rates in row i and the summation over all elements in each row must be equal to zero [19]. For instance, λ_{11} of the FB converter is equal to $-(\lambda_{12} + \lambda_{13} + \lambda_{14})$. As mentioned earlier, both SC and OC faults are considered in the reliability evaluations of the power electronic converters. According to statistics, the probability of SC fault is higher than that for OC fault in power electronic semiconductor devices [20]. Hence, if a switch or diode encounters a fault, the probabilities of 3/4 and 1/4 are assumed for SC and OC faults, respectively. Additionally, passive components are assumed to be only prone to SC faults due to the operational characteristics and this is enforced in the presented λ_{ij}s in Fig. 4. For instance, λ_{34} of the FB converter in Fig. 4(b) is calculated as

$$\begin{aligned} \lambda_{34} = \lambda_T + \lambda_{Co} &+ (2 \times 0.25\lambda_S) + (4 \times 0.75\lambda_S) \\ &+ (2 \times 0.25\lambda_D) + (3 \times 0.75\lambda_D) \end{aligned} \tag{6}$$

where, λ_S, λ_D, λ_T, λ_C and λ_{Co} are respectively the failure rates of the switch, diode, transformer, input blocking and output capacitors. Assuming the initial operating state to be healthy, the initial condition in (4) is expressed as

$$\left[P_1(0)\ P_2(0)\ \cdots\ P_{s+1}(0)\right] = \left[1\ 0\ \cdots\ 0\right] \tag{7}$$

Accordingly, the $P_i(t)$ would be assessed as

$$P_i(t) = \begin{cases} e^{\lambda_{ii} t}; & i = 1 \\ \dfrac{\lambda_{1i}}{\lambda_{11} - \lambda_{ii}} \left(e^{\lambda_{11} t} - e^{\lambda_{ii} t}\right); & i \neq 1 \end{cases} \tag{8}$$

Eventually, the MTTF is defined as follows:

$$MTTF = \int_{t=0}^{\infty} R(t)\,dt = \frac{-1}{\lambda_{11}} + \sum_{i=2}^{s} \frac{\lambda_{1i}}{\lambda_{11}-\lambda_{ii}} \left(\frac{1}{\lambda_{ii}} - \frac{1}{\lambda_{11}}\right) \quad (9)$$

where, λ_{ii} ($i = 1, \ldots, s$) and λ_{1i} ($i = 2, \ldots, s$) have negative and positive values, respectively. It is notable that the MTTF profile of the converters has the same behavior as its reliability curve, since the integral in (9) is with respect to t.

TABLE 1. Design parameters of each converter.

Converters	Components	D_B
FL (n = 0.75)	$L_m = 0.5\,mH$, $C_o = 250\,\mu F$	0.4
FL (n = 1)	$L_m = 1\,mH$, $C_o = 200\,\mu F$	0.43
FL (n = 1.25)	$L_m = 1.2\,mH$, $C_o = 180\,\mu F$	0.45
FW	$L_m = 1.5\,mH$, $C_o = 200\,\mu F$, $N_1 = n_1/n_2 = 1$, $N_3 = n_3/n_2 = 1$	0.4
IC, IS and IZ	$L = 1\,mH$, $L_m = 1.5\,mH$, $C = C_1 = C_2 = 47\,\mu F$, $C_o = 200\,\mu F$	0.51
FB, HB and PP	$L_{Lk} = 0.5\,mH$, $L_m = 5\,mH$, $C_1 = C_2 = C_o = 100\,\mu F$	0.3

IV. RELIABILITY ANALYSIS

We here present the reliability performance evaluation of the ISSDC-DC and IMSDC-DC power electronic converters under both DCM and CCM operation modes, which is centered on the steady-state and power loss models in [17]. The components design parameters and the DCM and CCM boundary duty cycle (D_B) are presented in Table 1. The initial values of $P_o = 100$ W, $f_s = 20$ kHz, $n = 1$, $t = 0.6 \times 10^6$Hr., and R = 100 Ω are assumed for the output power, switching frequency, transformer turn ratio, time duration and output load, respectively. We investigate how such parameters affect the overall reliability performance. The DCM and CCM duty cycles of D_{DCM} =1/3 and D_{CCM} =2/3 are selected for ISSDC-DC and D_{DCM} =1/6 and D_{CCM} =1/3 for IMSDC-DC converters. The minimum and maximum acceptable duty cycles are $D_{\min} = 0.1$ and $D_{\max} = 0.9$ for ISSDC-DC and $D_{\min} = 0.1$ and $D_{\max} = 0.5$ for IMSDC-DC converters. Sample semiconductor devices are assumed for the switch and diodes, where the forward ON state voltage drop of 1 V and drain-source ON-resistance of 0.049 Ω are considered for the switch, while they are 1.5 V and 0.023 Ω for the diode. The passive components are considered non-ideal. Additionally, the following need to be noted:

- Components failure rates are considered constants as time elapses, which is valid considering the elements to be in their useful life time [19]. The failure rates are formulated through the principles presented in [21], [22].
- As the components' power loss is different in the healthy and derated operating states of the IMSDC-DC converters, different failure rates corresponding to the healthy and derated operating states are considered.
- Throughout the presented analysis, t is in $Hours \times 10^6$.
- In order to highlight the role of transformers on the overall reliability of IDC-DC converters, the design, power loss and reliability assessment of the FL converter are repeated for $n = 0.75$, $n = 1$, and $n = 1.25$.

Based on the aforementioned operational principles, the Markov models, design procedure, and components characteristics, the reliability evaluations are classified as:

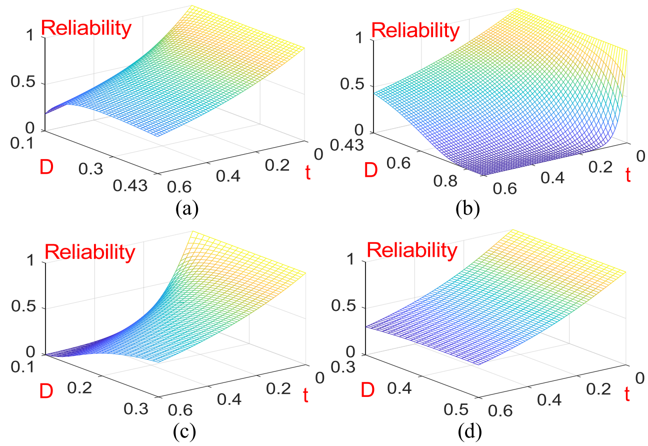

FIGURE 5. Reliability performance with respect to *D* and *t*. (a) DCM FL (n = 1). (b) CCM FL (n = 1). (c) DCM HB. (d) CCM HB.

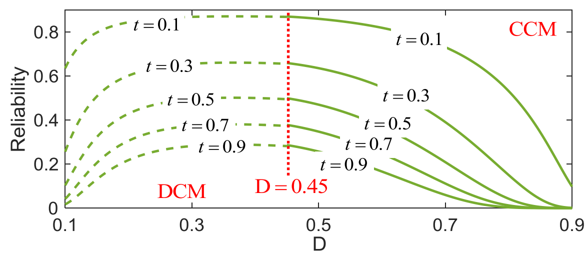

FIGURE 6. Reliability of FL (n = 1.25) with respect to D at different t values.

A. EFFECT OF DUTY CYCLE

In Fig. 5, reliability performance of the FL and HB converters are presented demonstrative of the ISSDC-DC and IMSDC-DC converters, respectively. The IDC-DC converters reveal a different response as D varies. Furthermore, the variations in t is reversely correlated with the reliability performance representing the component aging. The reliability of FL ($n = 1.25$) versus D variations under different t values is depicted in Fig. 6, in which the maximum reliability is achieved in DCM operation. The reliability performance of the IMSDC-DC and ISSDC-DC converters are compared in Fig. 7. One can see in Figs. 7(a, b) that the reliability performance of the HB and PP converters increases with D increments in both DCM and CCM operations, which is due to the lower input voltage requirement of these converters to reach the constant output power when D is higher—note the direct relation of D on the output voltage level. Hence, a lower

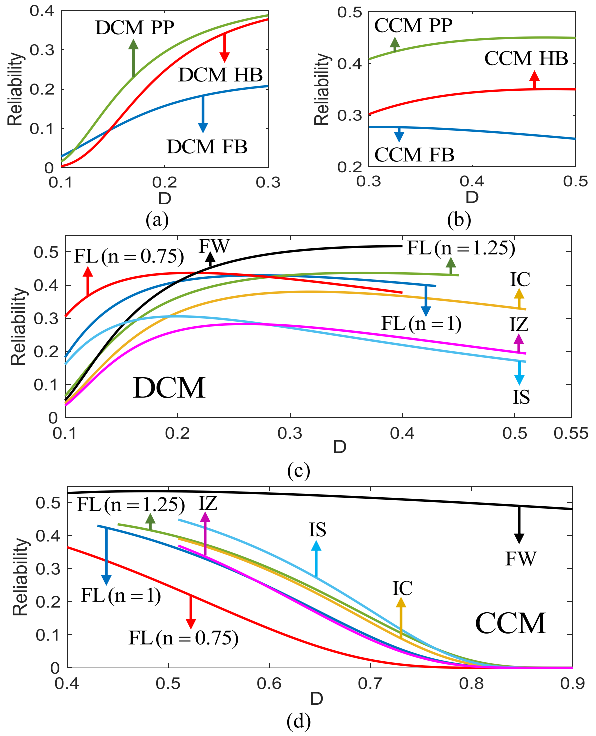

FIGURE 7. Reliability performance comparison with respect to D a $t = 0.6 \times 10^6$ Hours. (a, b) DCM and CCM IMSDC-DC. (c, d) DCM and CCM ISSDC-DC.

input voltage results in a lower voltage stress on the components and thus a higher overall reliability performance will be realized. On the other hand, higher power losses in the four power switches of the FB converter result in a degraded reliability when D is higher under CCM operation. In addition, PP converter has been observed to have the highest reliability performance among the IMSDC-DC converters. While the voltage stress in the primary-side switches in this converter is twice that of the FB and HB converters, PP has less number of switches and capacitors than FB and HB converters. The additional primary-side elements in the FB and HB converters operate in series with each other, which in turn, decrease their overall reliability. Furthermore, the voltage gain in an HB converter is half of that in the PP converter, reflecting the need for a higher input voltage and thus a higher component stress to satisfy the same output power. In Figs. 7(c) and (d), the FL ($n = 0.75$) and FW converters are observed to have the highest reliability performance when $0.1 < D < 0.21$ and $0.21 < D < 0.9$, respectively. Furthermore, the maximum reliability in the FL ($n = 0.75$), FL ($n = 1$), FL ($n = 1.25$), FW, IC, IS, IZ, FB, HB and PP converters is achieved in duty cycles of 0.21, 0.27, 0.36, 0.48, 0.32, 0.20, 0.26, 0.31, 0.47 and 0.47, respectively. Higher reliability performance of the FW converter is primarily due to its regenerative power to the input source from n_3 leading to a higher power efficiency.

In order to evaluate the effect of duty cycle on the reliability performance of the IDC-DC converters, Fig. 8 illustrates a sensitivity analysis with respect to D, where the sensitivities are assessed via $(dR(D)/dD).(D/R(D))$ at $t = 0.6 \times 10^6$ Hours. In Fig. 8, the direct (positive sensitivity) and inverse (negative sensitivity) relation of D with converter reliability are shown.

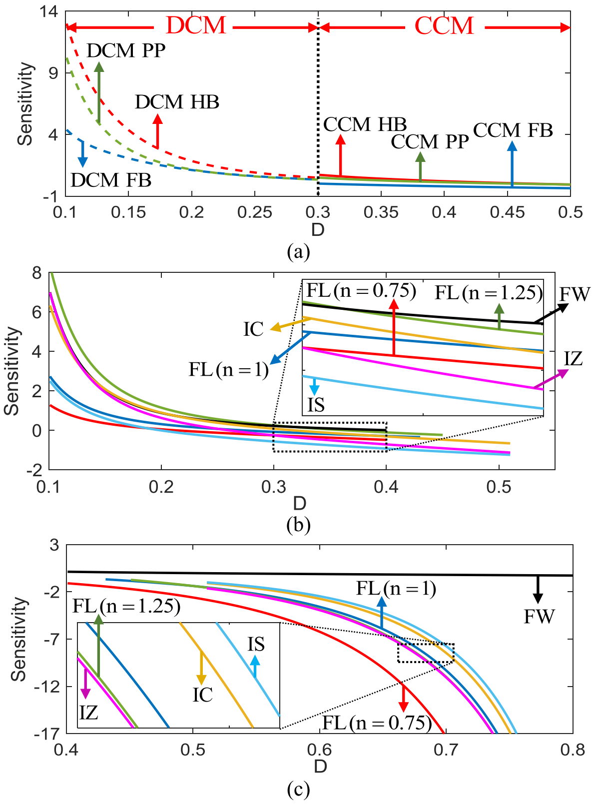

FIGURE 8. Sensitivity analysis of the converter reliability with respect to D at $t = 0.6 \times 10^6$ Hours. (a) IMSDC-DC. (b) DCM ISSDC-DC. (c) CCM ISSDC-DC.

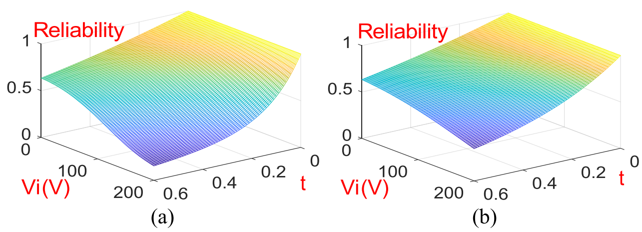

FIGURE 9. Reliability with respect to V_i and t. (a) DCM PP. (b) CCM PP.

B. EFFECT OF INPUT VOLTAGE

In some power electronic devices (e.g., photovoltaic power conditioning systems), the input voltage is variable, and therefore, it affects the converter's operational performance. In Fig. 9, the reliability performance of the PP converter is expressed under DCM and CCM operations. It can be seen that the DCM PP is attributed a lower reliability than the CCM PP, particularly when V_i is high. In Fig. 10, the reliability of IDC-DC converters is illustrated in a comparative view, where increments in V_i leads to increased components voltage stress, power loss and operational temperature, and therefore lower reliability performance. As shown in Fig. 10(a),

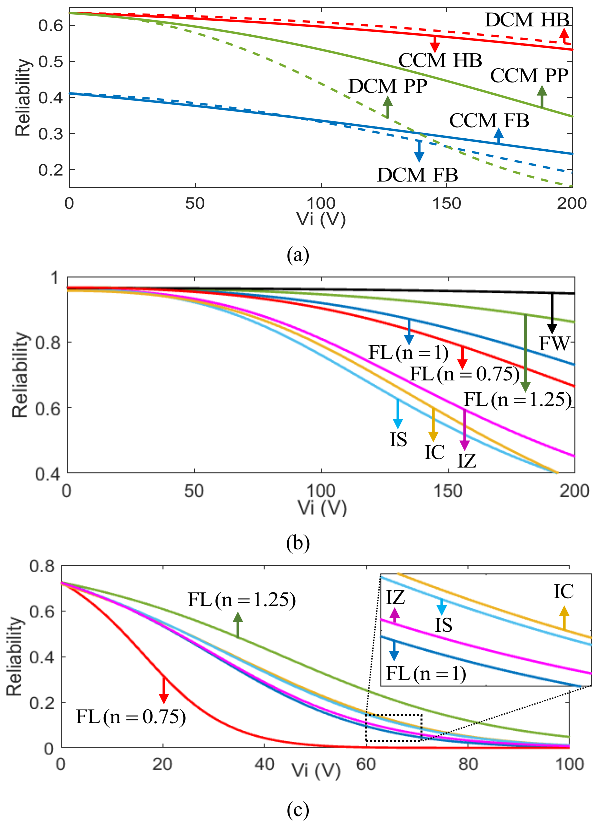

FIGURE 10. Reliability performance comparison with respect to V_i at $t = 0.6 \times 10^6$ Hours. (a) IMSDC-DC. (b) DCM ISSDC-DC. (c) CCM ISSDC-DC.

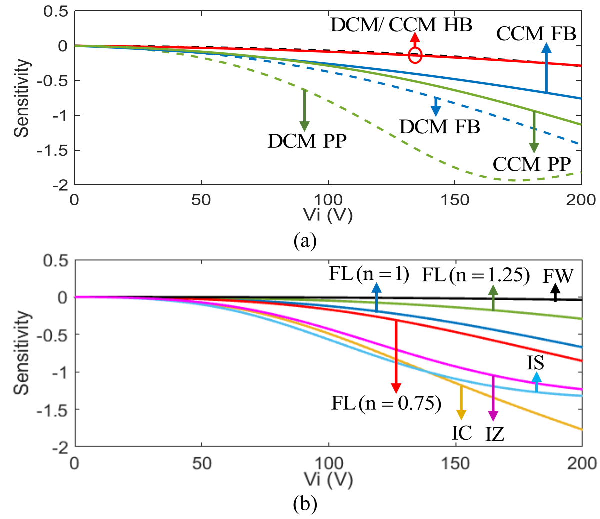

FIGURE 11. Sensitivity analysis of the converter reliability with respect to V_i at $t = 0.6 \times 10^6$ Hours. (a) IMSDC-DC. (b) DCM ISSDC-DC.

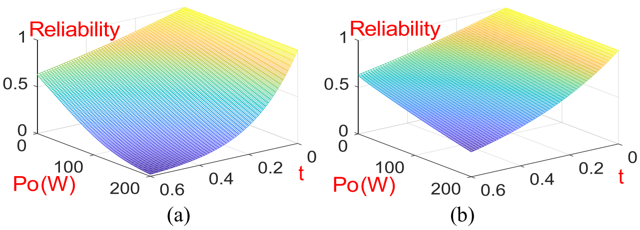

FIGURE 12. Reliability with respect to P_o and t. (a) DCM HB. (b) CCM HB.

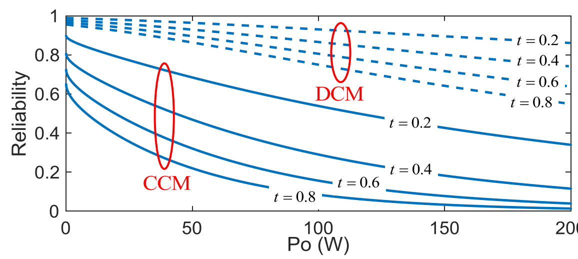

FIGURE 13. Reliability of FL ($n = 1$) with respect to P_o at different t values.

the DCM HB has the highest reliability among IMSDC-DC converters under a fixed duty cycle and variable V_i, owing to its lower total power loss of the switches and transformer. Moreover, the CCM FB, DCM FB and DCM PP have the lowest reliability under $0 < V_i < 90\,V$, $90\,V < V_i < 150\,V$ and $150\,V < V_i < 200\,V$, respectively. According to the comparisons on the ISSDC-DC converters in Figs. 10(b) and (c), the FW converter reveals the highest reliability as V_i varies. However, the IS and FL ($n = 0.75$) have the lowest reliability in DCM and CCM operations, respectively, which is mainly due to the high transformer failure rate in the former and high primary-side current stress in the latter. In addition, the reliability performance of the CCM IC and IS are found close due to similar operational principles. A reliability sensitivity analysis of the results in Fig. 10 is presented in Fig. 11. The DCM PP and DCM FW have the highest and lowest sensitivity to V_i variations, respectively.

C. EFFECT OF OUTPUT POWER

The output power range is also a key design parameter of power electronic converters. The effects of P_o variations on the reliability performance of IDC-DC converters are investigated in this section. The reliability performance of the DCM and CCM HB converters are demonstrated in Figs. 12(a) and (b), respectively. It can be seen that the operation of DCM HB converter is not optimal with the assumed design parameters in $t > 0.3 \times 10^6$ Hours and $P_o > 150$W. The reliability of FL ($n = 1$) with respect to P_o variations in different t values is expressed in Fig. 13, in which the aging is found as a key contributor on the CCM operation's reliability degradation.

The evaluated reliability of the IMSDC-DC, DCM ISSDC-DC and CCM ISSDC-DC converters are compared in Figs. 14(a), (b) and (c), respectively. In Fig. 14(a), the CCM HB and DCM PP are found to have the highest and lowest reliability performance among the IMSDC-DC converters when P_o changes. As examples of numerical results, the reliability performance of the CCM HB and DCM PP reaches 0.5165 and 0.1312 in P_o =50W and $t = 0.6 \times 10^6$ Hours, respectively. According to Figs. 14(b) and (c), the FW converter has the highest reliability in both DCM and CCM operation mode, while the IS and FL ($n = 0.75$) have the

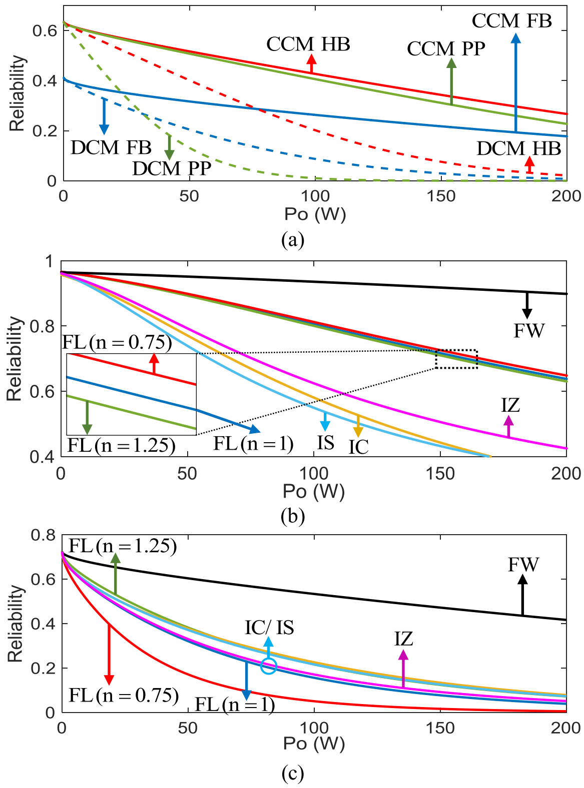

FIGURE 14. Reliability performance comparison with respect to P_o at $t = 0.6 \times 10^6$ Hours. (a) IMSDC-DC. (b) DCM ISSDC-DC. (c) CCM ISSDC-DC.

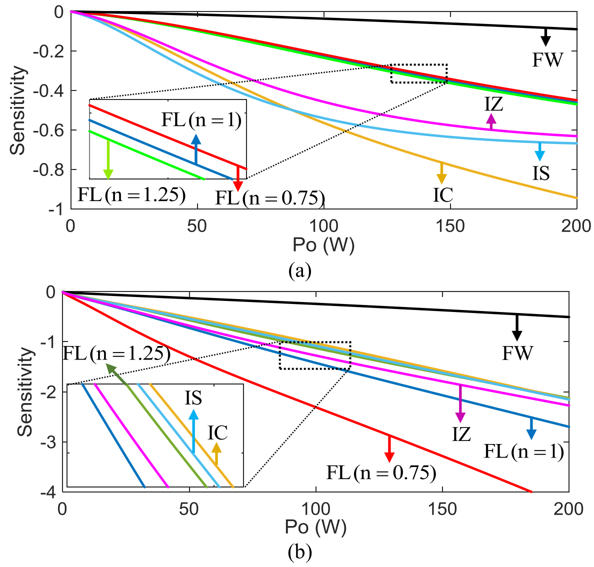

FIGURE 15. Sensitivity analysis of the converter reliability with respect to P_o at $t = 0.6 \times 10^6$ Hours. (a) DCM ISSDC-DC. (b) CCM ISSDC-DC.

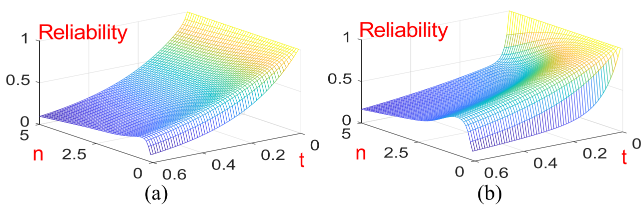

FIGURE 16. Reliability with respect to n and t. (a) DCM HB. (b) CCM HB.

lowest reliability among ISSDC-DC converters in DCM and CCM operations, respectively. This validates the fact that variations in P_o and V_i similarly influences the converter reliability performance. Moreover, Fig. 14 demonstrates that the CCM operation in all IMSDC-DC converters offers a higher reliability performance than DCM. In this case, the DCM operation requires a higher input voltage to feed a certain output power in a fixed duty cycle than the CCM. Hence, the additional primary-side switches in IMSDC-DC converters generate higher conduction loss than in the corresponding CCM operation. However, Figs. 14(b) and (c) demonstrate that the DCM operation offers a higher reliability among ISSDC-DC converters, primarily due to the higher switching loss in the ISSDC-DC converters when operating in CCM. A sensitivity analysis on the reliability performance of the ISSDC-DC converters under DCM and CCM operations is presented in Figs. 15(a) and (b), respectively. As one can see, the DCM/CCM FW are the least sensitive and DCM IC and FL ($n = 0.75$) are the most sensitive converters to P_o variations. Furthermore, the DCM FL ($n = 0.75$, 1, and 1.25) and CCM IC, IS and FL ($n = 1.25$) have similar sensitivity in DCM and CCM operations, respectively.

D. EFFECT OF TRANSFORMER TURNS RATIO

Selecting transformer's turn ratio within an optimal region significantly improves the overall reliability performance of the converter. Lower values of n (n:1) results in higher output voltage levels and higher primary-side semiconductors current stress. Therefore, a trade off must be pursued to determine its optimal region. In Fig. 16, reliability plots of HB converter are illustrated with respect to changes in n and t, where CCM operation reveals a higher reliability under a fixed P_o and varying n. In order to evaluate the effects of n and t on the ISSDC-DC converters, Fig. 17 shows that $n = 2.18$ is found as the boundary for the FL in which DCM and CCM have higher reliability in $0 < n \leq 2.18$ and $2.18 < n \leq 5$, respectively. This boundary is equal to 1.03, 1.05, 1.08 and 1.58 for the FW, IC, IS and IZ, respectively. Among the assessed converter topologies in Fig. 2 and Fig. 3, the FW is the only converter with three different windings in its transformer. Since n_2 is the most responsible for power transfer to the output load, $N_1 = n_1/n_2$ is considered in the evaluation process. However, in order to understand the role of $N_3 = n_3/n_2$ on the reliability performance, Fig. 18 is presented where it shows that the overall reliability of the FW converter is more sensitive to the changes in N_1 than in N_3 in both DCM and CCM operations.

In Fig. 19, the evaluated reliability of the IMSDC-DC and ISSDC-DC converters are compared. One can see in Fig. 19 that the reliability of all such converters reach an optimum point at a specific n, which are equal to 0.47, 0.83, 0.57, 0.1, 1.16, 0.51, 0.49 and 0.45 for the DCM FL, FW, IC, IS, IZ, FB, HB and PP converters, respectively. These n values are 2.35, 1.48, 1.96, 2.18, 2.27, 1.14, 0.77 and 0.76 for the

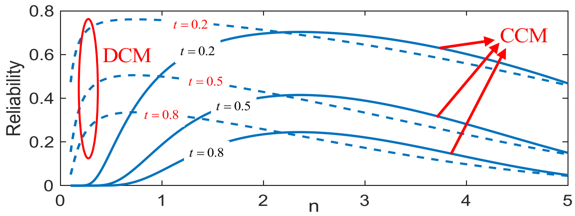

FIGURE 17. Reliability performance of FL with respect to *n* at different *t* values.

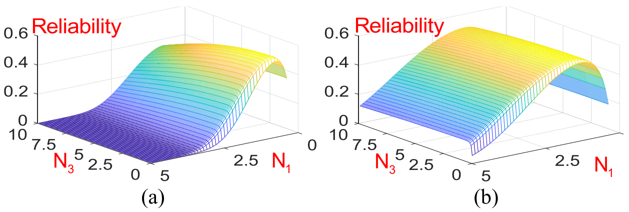

FIGURE 18. Reliability performance of the FW converter with respect to N_1 and N_3. (a) DCM. (b) CCM.

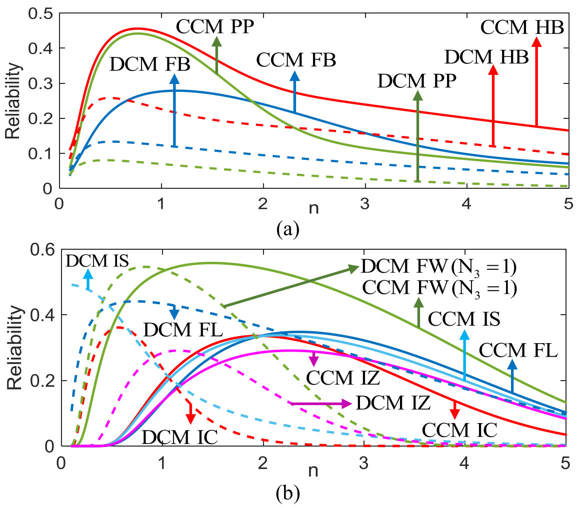

FIGURE 19. Reliability performance comparison with respect to *n* at $t = 0.6 \times 10^6$ Hours. (a) IMSDC-DC. (b) ISSDC-DC.

corresponding converters in their CCM operation. Moreover, in order to evaluate the impact of n on the reliability of IDC-DC converters in details, Fig. 20 shows a comparison of the reliability sensitivities. Positive and negative sensitivity values confirm a direct and inverse effect of n on reliability performance. In addition, the zero-crossing points of the sensitivity curves represent the optimal reliability points.

E. EFFECT OF COMPONENTS CHARACTERISTICS

Component characteristics along with the operational specifications play a main role on the overall reliability performance of a power electronic converter. In the presented reliability assessments, the failure rates corresponding to the power switches (λ_S) are the most sensitive to variations in the operational characteristics. Therefore, some power MOSFETs of the IRFP4xxxPbF family with different characteristics are selected to be further assessed in IDC-DC converters. Among such characteristics are the drain-source breakdown voltage, drain-source ON-resistance, output capacitor and turn-on and turn-off delay times. The results are presented in Table 2 and Table 3 for both DCM and CCM operations. Note that since the IMSDC-DC converters have several derated operating states with different power losses and failure

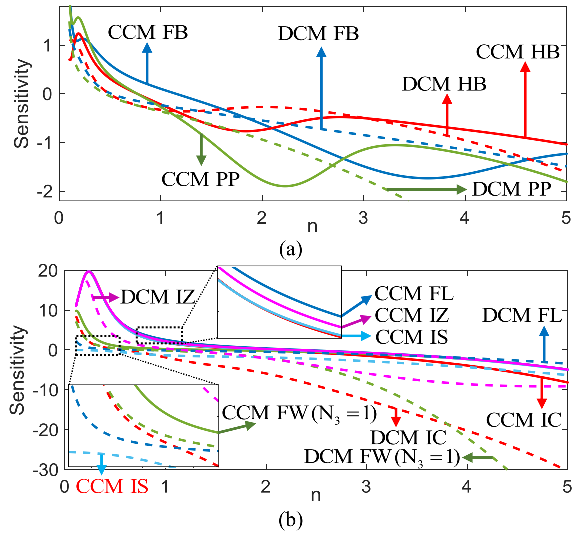

FIGURE 20. Sensitivity analysis of the converter reliability with respect to *n* at $t = 0.6 \times 10^6$ Hours. (a) IMSDC-DC. (b) ISSDC-DC.

TABLE 2. Failure rates of the selected power switches in IMSDC-DC. (Failures per 10^6 Hr.)

		Converter	IRFP4xxxPbF Power MOSFETs					
			4242	4232	4229	4137	4668	4868
DCM	State 1	FB	1.38	1.55	1.20	1.05	2.06	1.61
		HB	1.61	1.84	1.36	1.16	2.52	1.91
		PP	6.48	8.21	4.47	3.20	12.8	8.37
	State 2	FB	0.82	0.89	0.75	0.70	1.05	0.90
		HB	0.91	0.99	0.81	0.74	1.21	1.01
		PP	2.40	2.91	1.79	1.41	4.27	2.94
CCM	State 1	FB	0.71	0.71	0.75	0.74	0.79	0.77
		HB	0.92	0.97	0.91	0.86	1.16	1.04
		PP	0.92	0.97	0.91	0.86	1.16	1.04
	State 2	FB	0.64	0.66	0.65	0.63	0.72	0.69
		HB	0.68	0.71	0.68	0.65	0.79	0.73
		PP	0.96	1.05	0.88	0.80	1.29	1.08

TABLE 3. Failure rates of the selected power switches in ISSDC-DC. (Failures per 10^6 Hr.)

Converters		IRFP4xxxPbF Power MOSFETs					
		4242	4232	4229	4137	4668	4868
CCM	FL(n=0.75)	3.35	3.09	4.40	3.99	3.94	4.18
	FL(n=1)	2.29	2.19	2.93	3.00	2.79	2.86
	FL(n=1.25)	1.83	1.79	2.26	2.29	2.28	2.27
	FW	0.91	0.92	1.02	1.02	1.07	1.05
	IC, IS, IZ	2.94	2.19	2.93	3.03	2.79	2.86
DCM	FL(n=0.75)	0.89	0.92	0.88	0.84	1.09	0.98
	FL(n=1)	1.07	1.10	1.13	1.11	1.33	1.23
	FL(n=1.25)	1.12	1.18	1.11	1.04	1.46	1.28
	FW	0.91	0.95	0.90	0.86	1.14	1.02
	IC	1.45	1.50	1.31	1.27	1.65	1.49
	IS	1.10	1.12	1.18	1.16	1.34	1.27
	IZ	1.31	1.32	1.18	1.13	1.52	1.35

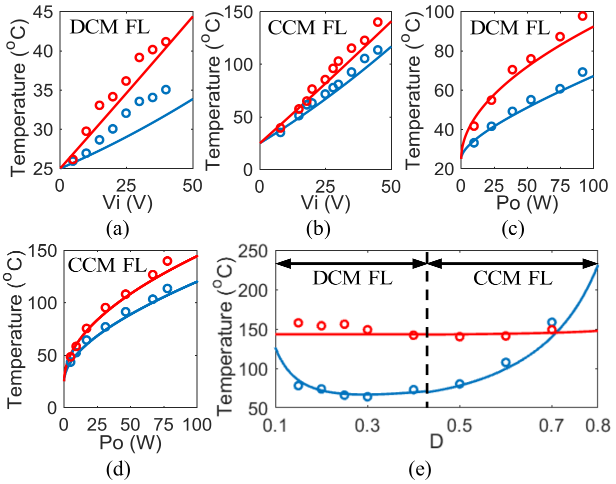

FIGURE 21. **Comparison of switch and diode experimental and theoretical thermal tests in the FL converter with respect to: (a, b) Input voltage. (c, d) Output power. (e) Duty cycle.**

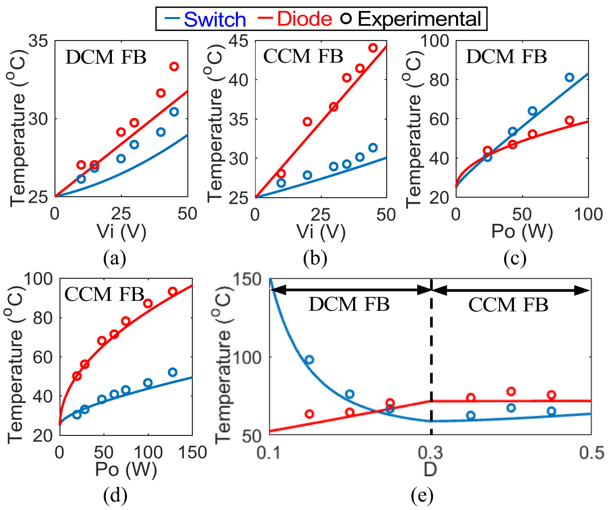

FIGURE 22. **Comparison of switch and diode experimental and theoretical thermal tests in the FB converter with respect to: (a, b) Input voltage. (c, d) Output power. (e) Duty cycle.**

rates, the λ_S values are tabulated for state 1 (healthy) and state 2 (derated state under OC faults on switches). Analysis of Table 2 and Table 3 reveals that all the aforementioned operating parameters of a switch differently affect the λ_S. Moreover, the type of the analyzed converter is determinative in λ_S. In other words, a comprehensive assessment framework is needed to evaluate the λ_S taking into account the effects of all the aforementioned parameters along with the converter operational characteristics. The results comparison demonstrates higher λ_S values for the DCM operation than for the CCM in IMSDC-DC converters, while it is the reverse for the ISSDC-DC converters.

V. EXPERIMENTAL RESULTS

As it is clear, thermal test of the power electronic converters reflects their reliability specification. Hence, some thermal tests are performed on the FL and FB converters, as examples of the ISSDC-DC and IMSDC-DC converters, and the results are compared with the theoretical analytics in Figs. 21 and 22. According to these figures, the experimental observations closely match the theoretical analyses, which verify the effectiveness of the proposed analytics for reliability evaluation of IDC-DC converters in both DCM and CCM.

VI. CONCLUSION

This paper has presented comprehensive reliability assessment and sensitivity evaluations of the IDC-DC converters and compared the role of various factors (e.g., duty cycle, input voltage, output power, transformer turns ratio, time duration and components characteristics) on the converters' overall reliability performance. The evaluations were conducted taking into account both DCM and CCM operations and under both OC and SC fault scenarios on the converter components. We classified the IDC-DC converters into the ISSDC-DC and IMSDC-DC converters, where Markov model was employed along with the components characteristics and converters operational principles to formulate the reliability metrics. We comprehensively presented the self-embedded fault tolerance capability of the IMSDC-DC converters against the OC fault scenarios on some particular components, which was further validated via experimental tests. It was found that increments in the input voltage and output power have reverse contribution on the converter's reliability performance. An optimal point in the converter's reliability performance of each IDC-DC converter was evaluated in terms of duty cycle and transformer turns ratio. Moreover, the CCM operation in IMSDC-DC converters was found more reliable under most operational conditions, while the ISSDC-DC converters revealed a higher reliability performance in DCM operation. Furthermore, the forward converter is found the most reliable converter among the IDC-DC class of converters in most cases and when evaluated under the same operational conditions.

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