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System-Level Reliability-Oriented Power Sharing Strategy for DC Power Systems

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***Abstract*— Power converters are one of the failure sources in modern power systems, and hence driver of maintenance and downtime costs, which should be reduced by reliable design, control and operation of converters. This paper proposes a power sharing control strategy for evenly distributing the thermal stresses among dc converters in dc microgrids, and consequently enhancing the overall system reliability. The aim of this paper is to extend the aging process of failure prone converters by adjusting their loadings. The proposed approach employs the prior experienced thermal damages on the converter's fragile components in order to adjust its contribution on demand supply. According to the proposed strategy, the higher the thermal stress on a converter is, the lower the power it will supply. As a result, the overall system reliability will be improved. A numerical case study on a dc microgrid is presented to illustrate the effectiveness of the proposed power sharing strategy. Moreover, experimental tests are provided to demonstrate the applicability of the reliability-oriented power sharing method.**

Index Terms* – *lifetime, reliability, dc power system, power sharing, system-level reliability, thermal stress.

I. INTRODUCTION

Energy is the most important issue encountering the world today. Hiking in energy demands together with the environmental and security concerns require sustainable and low-carbon energy technologies. Microgrid and smart-grid technologies have become key enabling solutions for establishing sustainable energy networks. In particular, thanks to its high flexibility, efficiency, availability and profitability, dc microgrids have been gaining increasing interest in recent years. Meanwhile, power electronics plays a considerable role in the energy conversion process and accordingly in the microgrids and smart-grids. Growing use of power electronics in microgrids and smart-grids pose new challenges to the reliable and available operation of modern energy delivery systems. For instance, almost one-fourth of failure rates in wind turbines comes from the power converter hardware [1]. Hence, the reliability of power electronic converters has gained significant interest recently.

So far, different efforts have been carried out for reliability assessment and enhancement in power electronics. This concept can be generally categorized in three hierarchical levels; (a) Hierarchical Level 1 (HL1), i.e., component/device level, (b) HL2, i.e., converter level, and (c) HL3, i.e., system level as shown in Fig. 1. The component/device level (HL1) efforts use Physics-of-Failure (PoF) analysis for converter components such as semiconductors, capacitors, Printed Circuit Boards (PCB), inductors, gate drives in order to understand the reliability model of components for manufacturing high reliable products. These reliability models are employed in order to Design for Reliability (DfR) at converter level (HL2) aiming at achieve a desired lifetime under specific operating conditions [2]–[9]. Moreover, active thermal control for an individual converter such as an adaptive switching frequency for thermal stress reduction [8] can extend its lifetime. System level analysis (HL3) has been presented in order to model and improve the reliability of multiple power converters operating in a power system [10]. Suitable power converter design considering the mutual impact of other converters as well as appropriate control system can improve the system level reliability of power electronic based power systems [11].

In HL1, the state-of-the-art PoF analysis has been widely represented for semiconductor switches and electrolytic capacitors rather than other components. These two components not only serve as the main functional element in a power converter but also they are the most fragile components [8], [12]–[15] in a power electronic system. Therefore, their lifetime significantly affects the whole system reliability. According to the PoF reliability analysis, as power electronic devices are exposed to thermo-mechanical stress, thermal cycling is identified as one of the major critical stressors [15]–[20]. Following the developed empirical models [16], [18], lifetime of power semiconductor devices is closely related to the peak-to-peak variation of their junction temperature (i.e., ΔT_j). Moreover, the lifetime model of capacitors attributes to the hot-spot temperature. Hence, any attempt to reduce the junction temperature swing, and/or hop-spot temperature can increase the lifetime of these failure prone components.

One of the approaches in improving lifetime of semiconductor switches, which is attributed to the HL2, is

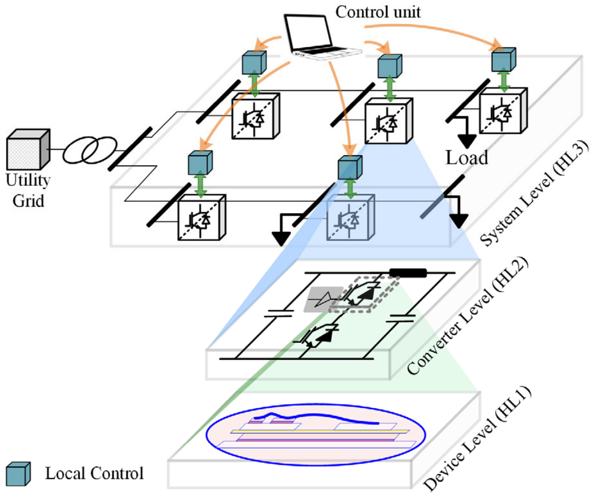

Fig. 1. Hierarchical reliability assessment from device-level (HL1) to system level (HL3) – HL: Hierarchical Level.

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known as active thermal management for reliability [8], [17]. For instance, appropriate modulation strategy [3], [7], reactive power control [4], active power control [4], [5], and adaptive switching frequency [8] are some active thermal stress reduction approaches. Furthermore, hot-spot temperature reduction for capacitors can be carried out by interleaving converters [21], [22] and proper allocation on converter cabin for suitable heat transfer.

An effective technique to reduce the stress in a power converter, and consequently improve the system reliability, is to reduce the thermal cycling either by diminishing the temperature swing or by reducing the mean temperature value. Thermal cycling of a converter is a result of different dynamics including climate change, control, device switching, and loading [13]. Modification of converter loading can easily be performed by modifying the power reference of the converter, hence, the thermal cycling can be actively controlled. The power reference of the converters is associated to the power sharing control in HL3. So far, conventional power sharing strategies rely on converters rated power in order to prevent their overloading. For instance, voltage droop methods [23], [24] and frequency droop techniques [25] are presented for power sharing in dc microgrids. In these approaches, the converter loading is proportional to the corresponding rated power, which is attributed to the mean temperature of the devices. While the stress of the devices significantly depends on the power cycling. Hence, the conventional droop control may prevent the overloading of the converters while it cannot prevent its overstressing, and consequently its lifetime. Furthermore, supervisory based droop controller are also presented in [26] for power loss reduction of converters; consequently improving the overall system efficiency. A cost-based droop approach is also introduced in [27] for power sharing control by considering the operational cost of sources. In the aforementioned approaches, even the converter loading remains under the rated value, it cannot guarantee to keep the stresses under the designed strength values. Furthermore, any unexpected factor such as ambient temperature rising or cooling system deficiency causes unwilling damage on the converter components even though it is operating under rated power. Hence, the reliability is an important challenge of power converter operation in multi-converter systems.

A reliability-oriented power sharing strategy between two dc-dc converters with different parameters has been presented in [28], while the reliability of converters are just attributed to the semiconductors. Furthermore, lifetime-based power routing scheme among parallel connected dc-dc converters in a more electric aircraft is presented in [29] considering the impact of power switches. It also considers the same converter topologies operating in parallel. However, in practice, other components such as diodes and capacitors as well as converter topology and its application may also have significant impact on the overall system reliability [22].

This paper proposes a general reliability-oriented power sharing strategy in HL3 for power electronic based power systems with different converter topologies. The proposed approach considers the impact of two failure prone components, i.e., electrolyte capacitors and semiconductors, while the approach can easily be modified to take into account any other components. According to the proposed control strategy, the reliability of power systems can actively be monitored and the wear-out aging process of weak converters can be postponed. Hence, the overall reliability can be improved. The proposed power sharing approach is applied for a dc microgrid due to the rising interest on dc grids in recent years. In the following, the proposed reliability-oriented power sharing scheme is presented in Section II. Simulations and numerical analysis are validating the proposed strategy and it is provided in Section III. Section IV demonstrates the viability of the reliability-based control for dc power systems implemented in a laboratory prototype. Finally, the outcomes are summarized in Section V.

II. PROPOSED DROOP APPROACH

The proposed load sharing approach aims to improve the power system reliability by equalizing the consumed lifetime of converters. The consumed lifetime of converters is reciprocally equal to the accumulated thermal damage on the corresponding components. By monitoring the temperature of fragile components and estimating the thermal damage of the converters, the weakest ones will be identified. The power management unit, thus, reshapes the damage of the converters by a proper power sharing strategy. Hence, the converters with high damage will supply lower power and the remaining load power should be compensated by the converters with less damage. In the following, the reliability modeling and subsequently proposed power sharing approach are explained.

A. Converter reliabiltiy modeling

According to [20], [28], the converter reliability depends on its loading profile and climate conditions. These operating conditions cause aging of converter components, which is called wear out in reliability engineering. Furthermore, capacitors and semiconductor switches are two of the most vulnerable components of power electronic converters [15], [20], [22], [28], [30]. The well-known lifetime model for semiconductor switches is represented in (1), where the number of cycles to failure, *N*, the switch can withstand without failure, depends on the minimum junction temperature T_{jm}, junction temperature swing ΔTj, and its heating time t_{on} [31], [32] given as:

$$N = A \cdot \Delta T_j^{\alpha} \cdot \mathbf{exp}\left(\frac{\beta}{T_{jm}+273.15}\right) t_{on}^{\ \gamma} \tag{1}$$

where A, α, β, and γ are the constants obtained from long-term lifetime tests [31]. Therefore, the aging of a semiconductor switch is calculated based on its power cycling as:

$$D^{(sw)} = \sum_{t} \frac{n_t}{N_t} \tag{2}$$

where $D^{(sw)}$ is the damage on the switch with n_t power cycles during period t. N_t is the number of cycles to failure due to the applied power cycle with corresponding T_{jm}, ΔT_j, and t_{on} which is obtained from (1). This equation can be employed to estimate the aging of power switches such as Insulated-Gate Bipolar Transistor (IGBT) and diode.

Furthermore, the aging of the electrolytic capacitors can be calculated employing the lifetime model presented in (3) [33] as:

$$L_w = L_r \cdot 2^{\frac{T_r - T_w}{n_1}} \left(\frac{V_w}{V_r}\right)^{-n_2} \tag{3}$$

in which L_r, V_r, and T_r, being the rated lifetime, voltage and hot-spot temperature of capacitor and L_w, V_w, and T_w, are the consumed lifetime, voltage and temperature under working conditions. If the capacitor operates under these conditions for the time of ΔL_w, the damage $D^{(cap)}$ on the capacitor is obtained by (4) as:

$$D^{(cap)} = \sum_t \frac{\Delta L_w}{L_{w,t}} \tag{4}$$

Finally, the total damage per component, D, in a converter can be calculated as:

$$D = \frac{1}{M^{(sw)} + M^{(cap)}} \left(\sum_j^{M^{(sw)}} D_j^{(Cap)} + \sum_j^{M^{(cap)}} D_j^{(Switch)} \right) \tag{5}$$

$M^{(cap)}$ and $M^{(sw)}$ are the total number of capacitors and switches in the converter. As it is already mentioned, this paper considers two failure prone components in the reliability modeling due to the existence of the corresponding lifetime models. However, this strategy can include the impact of other components in general by modifying (5) as:

$$D = \frac{1}{\sum_X M^{(X)}} \sum_X \sum_j^{M^{(X)}} D_{t,j}^{(X)} \tag{6}$$

where X denotes a component type such as capacitor, switch, inductor, etc, and $M^{(X)}$ is the number of component type X.

B. Propsed power sharing scheme

The proposed power sharing approach controls the output power/current of converters taking into account their damages during operation. At first, the system is operated with an equal power sharing among the converters. After a certain period, e.g., one month, the converters damage in the last period and the accumulated damage from the starting point are calculated. Afterwards, the load power is shared among the converters such that the converter with higher damage should supply lesser power for the coming period and vice versa.

The proposed power sharing approach is shown in Fig. 2. The converter operating conditions, i.e., output current I_{out}, dc link voltage, V_{dc} and ambient temperature, T_a are collected during a certain operating period (e.g., one month) and then translated into the thermal variables including semiconductor switches' junction temperature and capacitors' hot-spot temperature.

The electro-thermal mapping procedure is shown in Fig. 3. The converter load (I_{out}), voltage (V_{dc}) and ambient temperature (T_a) is used as inputs and the converter is simulated under different operating conditions in PLECS software. The thermal model of components including thermal impedances, on-off switching energy, and V-I curves given in the component datasheet are employed to calculate the component loss and temperature by PLECS. Another approaches for estimating the junction temperature of semiconductor devices are discussed in [34], [35]. The corresponding temperatures are stored in look-up tables for different operating conditions in order to estimate the temperature of devices in the power sharing control loop as shown in Fig. 2.

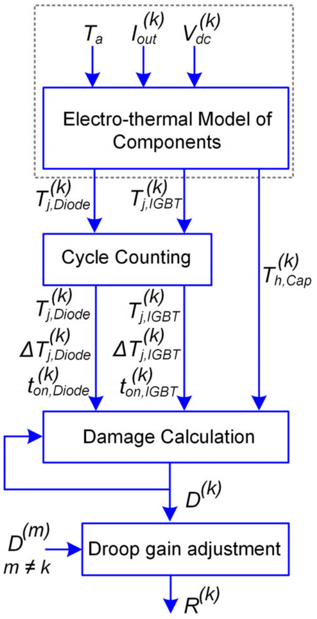

Fig. 2. Proposed lifetime-oriented droop gain adjustment for k^{th} converter.

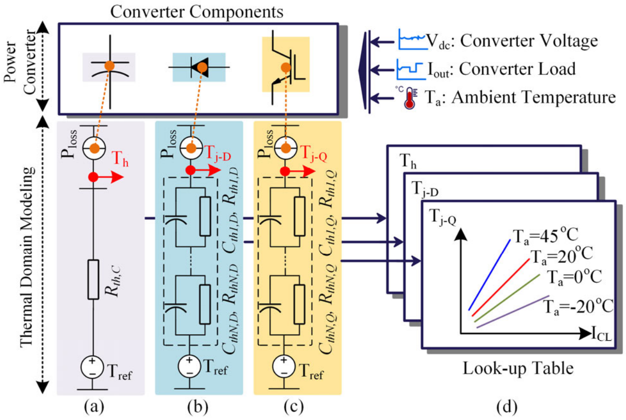

Fig. 3. Electro-thermal mapping procedure.

In some specific applications, the hardware setup is equipped with temperature measurements for health and condition monitoring purposes [36]. Thereby, the measured temperatures can directly be employed, and hence, the electro-thermal translation procedure is not required. For general approaches such as dc microgrids, junction temperature measurement may impose extra costs and also the reliability of measurements should also be taken into account. Therefore, this paper estimates the junction temperature based on electro-thermal mapping. Once the junction temperatures are obtained, temperature swing and its heating time can be calculated by a cycle counting algorithm. Afterwards, the damage on the

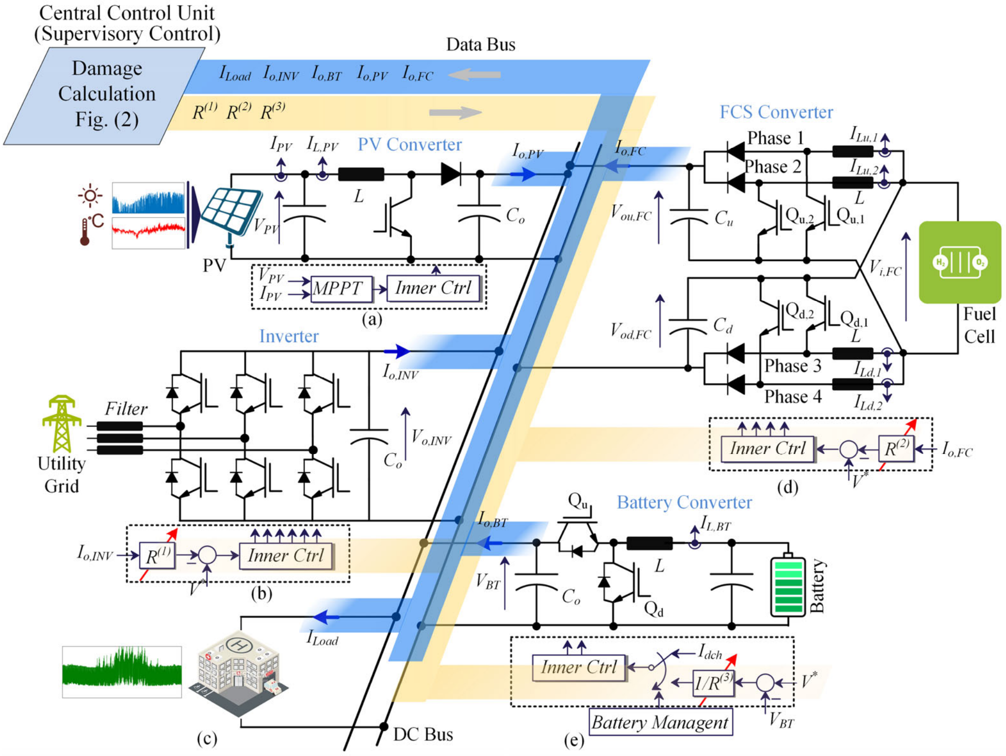

Fig. 4. Schematics of the dc grid; (a) PV converter, (b) grid connected inverter, (c) load, (d) fuel cell stack converter, and (e) battery converter.

Table I. Power converter parameters – S: Laplace operator.

Converter Parameters	PV Converter	Inverter	FCS Converter	Battery Converter
Rated power	5 *kW*	5 *kW*	5 *kW*	5 *kW*
Switching frequency	20 *kHz*	20 *kHz*	20 *kHz*	20 *kHz*
Output capacitor	2×220 *μF* (C_o)	2×220 *μF* (C_o)	5×220 *μF* (C_u, C_d)	2×220 *μF* (C_o)
ESR per capacitor @ 100 Hz	0.35 Ω	0.41 Ω	0.24 Ω	0.41 Ω
Capacitor thermal resistance	19.5 *K/W*	19.5 *K/W*	28 *K/W*	19.5 *K/W*
Capacitor thermal time constant	10 *min*	10 *min*	10 *min*	10 *min*
DC inductor	1 *mH*	-	1 *mH*	1 *mH*
IGBT	IGB10N60T	IGB20N60H3	IGB15N60T	IGB15N60T
Diode	IDV20E65D1	IDV15E65D2	IDV20E65D1	IDV15E65D2
Battery capacity	-	-	-	2000 *Ah*
DC Bus voltage	400 *V*	400 *V*	400 *V*	400 *V*
Input voltage	220 – 320 *Vdc*	150 *Vac,rms* (@50 *Hz*)	72-110 *Vdc*	300-335 *Vdc*
Current controller	5+100/S	10+1000/S	0.1+20/S	5+100/S
Voltage controller	1.5+20/S	0.2+20/S	0.05+50/S	1.5+20/S
MPPT algorithm	perturb & observe	-	-	-
Sampling frequency	50 *kHz*	50 *kHz*	50 *kHz*	50 *kHz*

converter is computed according to (5). Moreover, the damage of the previous periods is added to the calculated damage in order to consider the converter degradation during the operation period. Finally, the power sharing among the converters is performed by employing an adjustable droop controller, where the droop gain of the k^{th} converter can be defined as:

$$R^{(k)} = \alpha \cdot R_o^{(k)} + (1-\alpha) \cdot \frac{D^{(k)}}{Max_j\{D^{(j)}\}} \tag{7}$$

in which R is the droop gain, R_o is the conventional droop gain, D is the converter damage, and α is a constant. R_o can be defined according to the rated power of converters or based on the operational costs of units. It is obvious that for α = 1, the power sharing is carried out based on conventional approach, while for $\alpha = 0$, the reliability-oriented power sharing is employed. Notably, the droop gains should be selected to ensure the stability of the system [37], [38].

The value of α makes it possible to compromise between first term, for instance, operational costs and the second term, i.e., reliability. The droop gain is generally presented in (7) and it can be modified based on the control strategy. Since the main focus of this paper is on the reliability, the conventional droop control is compared to the proposed one to highlight the performance of the reliability-oriented power sharing approach. In this paper, the price of converters is considered to be almost identical, and hence, the replacement and/or maintenance cost analysis is not covered in this paper.

In this approach, the load sharing among the converters is performed based on thermal stress on the components, hence by controlling the converter loading, the converters damages can be approximately equalized and the overall system reliability due to the wear out if components can be improved.

This control part can be implemented either in a distributed fashion or a centralized one. In the distributed approach, the converters communicate their damages with other converters. While in the centralized approach, all operating data can be collected in a central control unit and the adjusted droop gains are sent to the converters, for example, one time per month. Since, the droop gains are adjusted on monthly basis, it does not require a high bandwidth communication system. Therefore, the control system performance, i.e., stability, does not rely on communication system. Hence, in the case of loss of communication link, the control system will continue with the previse droop gain. As a result, the stability and reliability of the system is independent of the communication system.

Notably, the proposed approach can be applied for ac and dc microgrids by properly calculating the converters damage and modifying the power sharing among the converters. For ac microgrids, the frequency droop gains should be adapted according to the thermal damages. This paper, applies the proposed strategy for dc microgrids and the evaluations are carried out on a dc microgrid as shown in Fig. 4. Next section will exemplify the effectiveness of the proposed power sharing approach.

III. SIMULATION AND NUMERICAL ANALYSIS

This section provides numerical analysis and long-term simulations to show the performance of the proposed control approach on a dc microgrid. The load sharing among inverter, battery and FCS converters in a dc microgrid as shown in Fig. 4 are controlled with conventional and proposed approaches. The specifications on the converters and system are summarized in Table I. The PV converter is always operating at Maximum Power Point Tracking (MPPT) mode, and the load is supplied by the inverter, FCS and battery. Furthermore, the inverter operates in the inversion mode injecting the power into the grid whenever the PV output power is higher than the load and the battery has high SOC. In the conventional droop approach, with $\alpha = 1$ in (7), and $R_o = 1\ \Omega$, the loading of inverter, FCS and battery converters should be equal if the SOC of the battery is high enough. Otherwise, the battery should be charged based on its energy management strategy. The result of power sharing within a year employing the mission profiles (see Fig. 5) is shown in Fig. 6. Furthermore, the load sharing results among the converters for the proposed approach with $\alpha = 0.5$ and $\alpha = 0$ are reported in Fig. 7 and Fig. 8 respectively. The impact of power sharing strategies is obvious in these figures. For instance, it is shown in Fig. 9 within a week where the converter loadings are changed by applying different power sharing strategies.

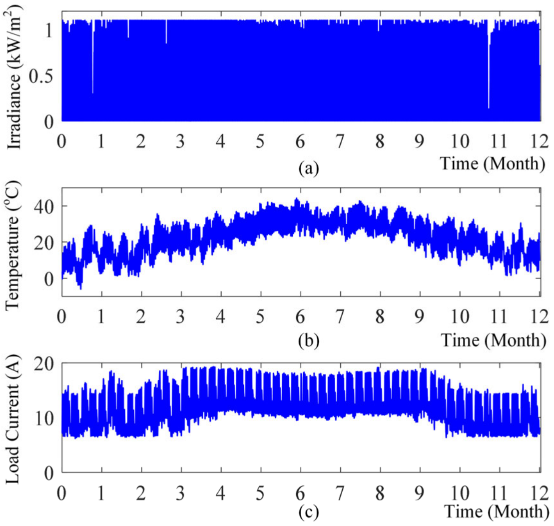

Fig. 5. Mission profiles; (a) solar irradiance, (b) ambient temperature, (c) load current.

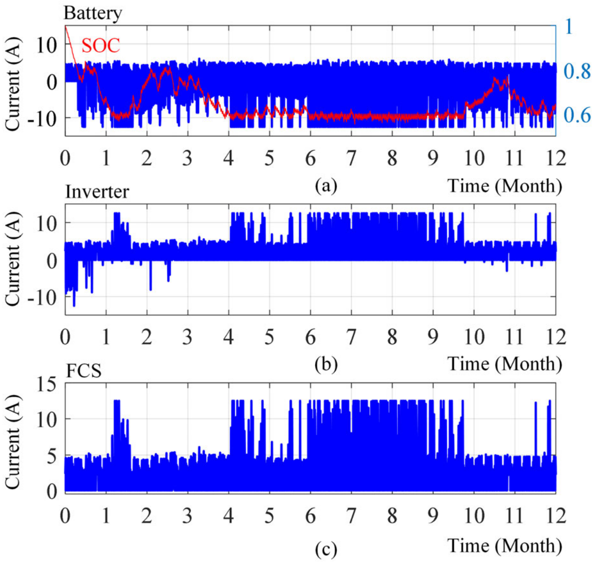

Fig. 6. Output current of converters; (a) Battery, (b) Inverter, and (c) FCS in conventional power sharing method, i.e., $\alpha = 1$.

As it is already mentioned, in the conventional approach with $\alpha = 1$, the droop gains are selected to be $R = 1$ and the corresponding damage on the converters are shown in Fig. 10 with solid-lines. It is clear that the damages on the FCS and battery converter are higher than for the inverter. Employing the proposed power sharing approach, based on a combination of reliability-oriented and conventional droop methods with $\alpha = 0.5$ as given in (7), results in reducing the FCS and battery

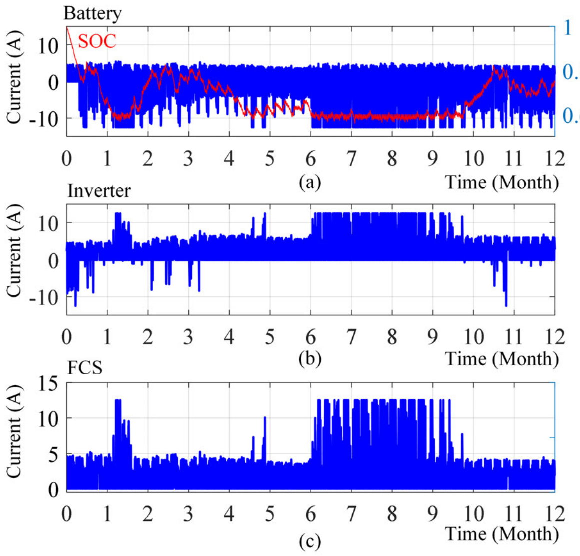

Fig. 7. Output current of converters; (a) Battery, (b) Inverter, and (c) FCS in a merged conventional and reliability-based power sharing method, i.e., $\alpha = 0.5$.

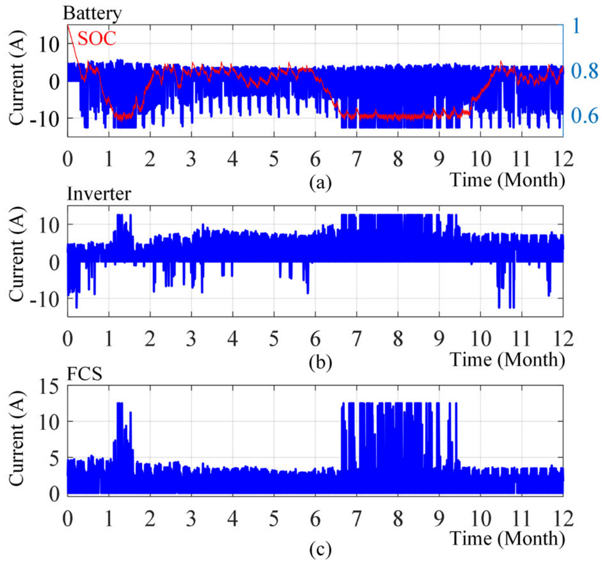

Fig. 8. Output current of converters; (a) Battery, (b) Inverter, and (c) FCS in reliability-based power sharing method, i.e., $\alpha = 0$.

converter damages and rising the inverter damage as shown in Fig. 10 with dotted-lines. Furthermore, the adjusted droop gains in this case is shown in Fig. 11 implying that the output current of the inverter should be increased by diminishing the inverter droop gain. Hence, its output current will be high resulting in reducing FCS and battery currents as shown in Fig. 9. Therefore, their damages are degraded as shown in Fig. 10.

Moreover, employing the reliability-based droop approach with $\alpha = 0$ further increases the inverter damage and reduces the battery and FCS damages as pointed out in Fig. 10. The corresponding droop gains are adjusted according to the converters damages as shown in Fig. 11 indicating more decrement in its droop gain. Consequently, the output current of the inverter will be increased as shown in Fig. 9. Therefore, employing the reliability-oriented power sharing approach to a good extent can equalizes the damage on the converters.

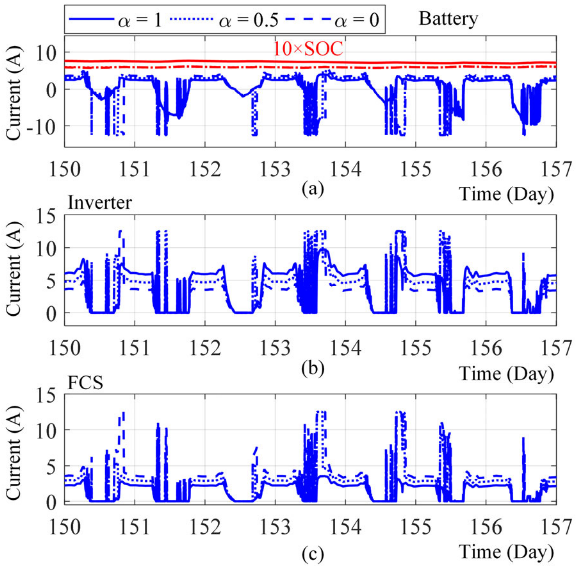

Fig. 9. Impact of power sharing schemes on the output current of converters; (a) Battery, (b) Inverter, and (c) FCS within a week.

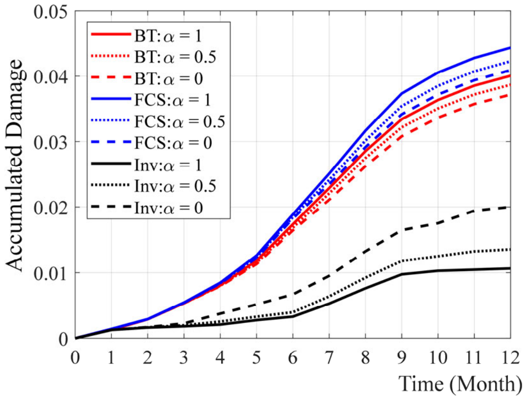

Fig. 10. Annual accumulated damage of the converters under different power sharing schemes.

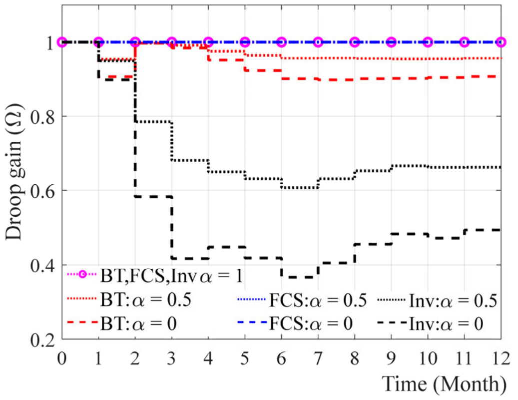

Fig. 11. Adjusted droop gains of converters under different power sharing schemes.

In order to show the performance of the proposed approach, the reliability of converters are estimated by employing a mission profile based reliability assessment method [22], [30]. Fig. 12 to Fig. 14 show the components reliability of the inverter, battery and FCS converters with different power sharing strategies. Following these results, the capacitor has the

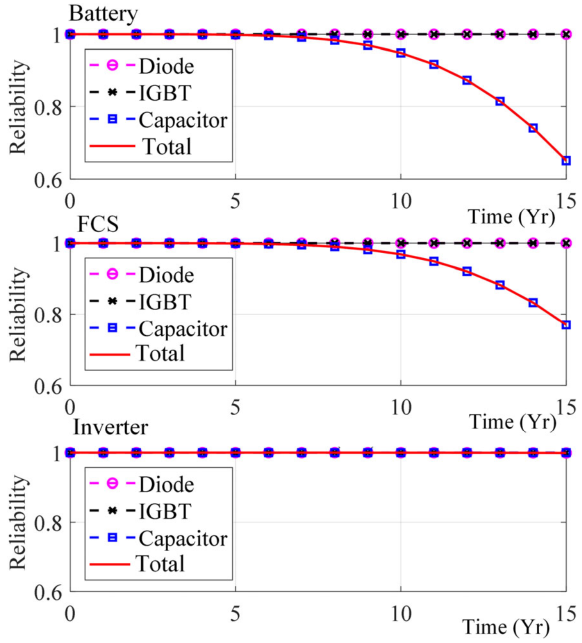

Fig. 12. Contribution of converter components on its reliability under conventional power sharing scheme, i.e., $\alpha = 1$.

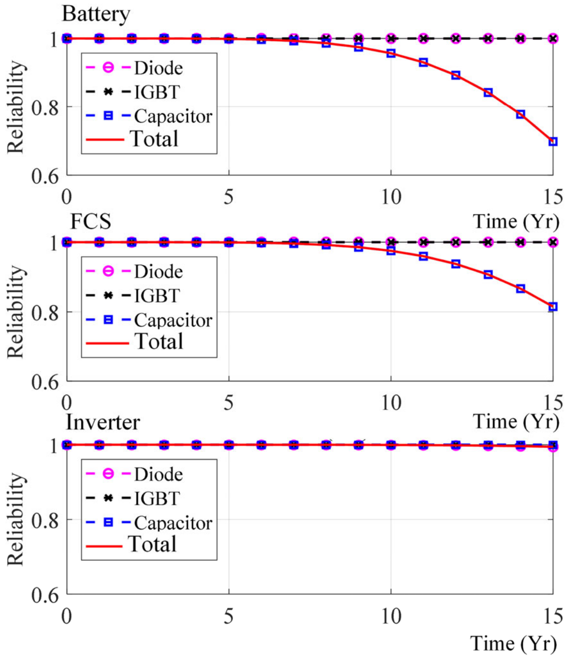

Fig. 13. Contribution of converter components on its reliability under merged conventional and reliability-based power sharing scheme, i.e., $\alpha = 0.5$.

dominant impact on the reliability of battery and FCS converters, while the inverter diodes limit its reliability. The temperature of these components is shown in Fig. 15. As shown in Fig. 15(a) and (b), the proposed method with $\alpha = 0$ decreases hot-spot temperature of capacitors compared to the conventional approach with $\alpha = 1$. Notably, the junction temperature of diodes in the inverter is increased as shown in Fig. 15(c). This implies that the reliability of battery and FCS converters are improved, while the reliability of inverter is decreased by employing the proposed strategy.

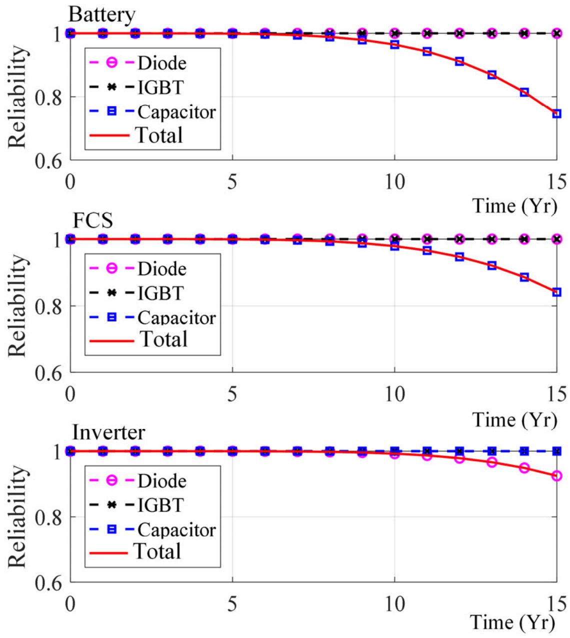

Fig. 14. Contribution of converter components on its reliability under reliability-based power sharing scheme, i.e., $\alpha = 0$.

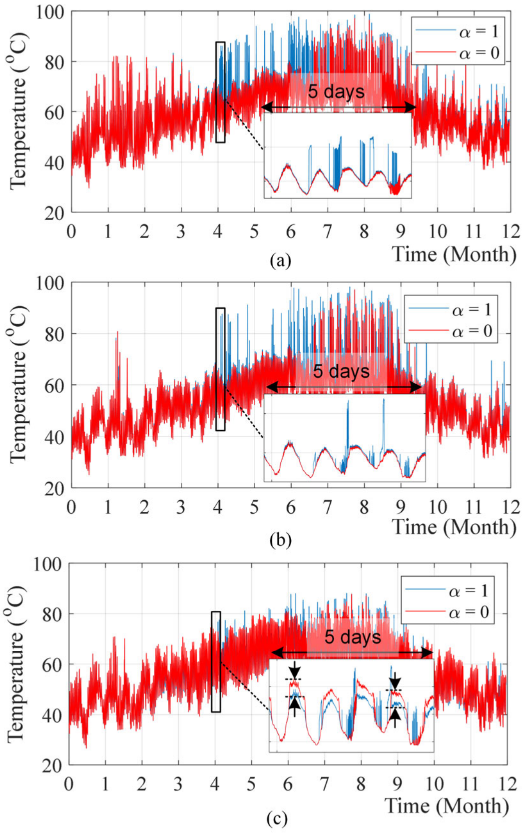

Fig. 15. Illustration of impact of conventional and reliability-based power sharing schemes on the (a) capacitor hot-spot temperature of battery converter, (b) capacitor hot-spot temperature of FCS converter, and (c) diode junction temperature of inverter.

The overall reliability of the converters employing series network reliability analysis, i.e., series connection of capacitors, diodes and IGBTs in terms of reliability, is shown

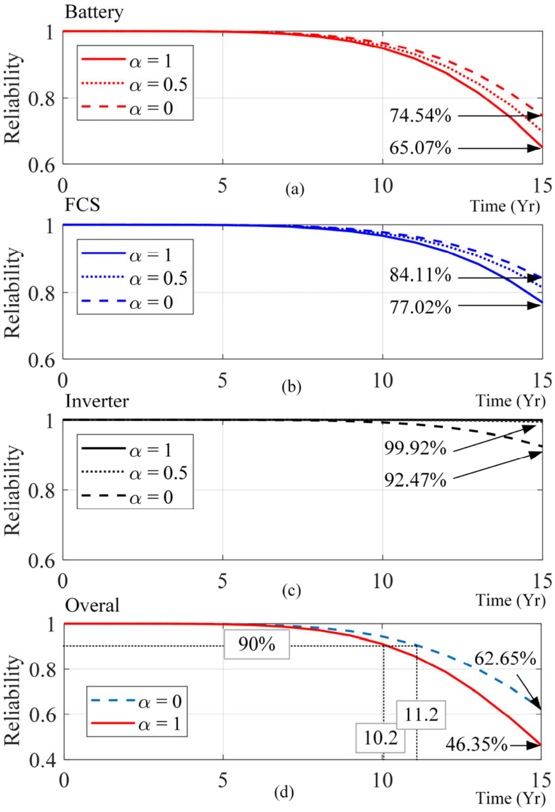

Fig. 16. Total converter reliability under different power sharing schemes; (a) battery converter, (b) FCS converter, (c) inverter, and (d) overall microgrid reliability.

in Fig. 16. According to Fig. 16(a)-(c), the reliability-oriented power sharing strategy will improve the reliability of battery and FCS converters, while deteriorating the inverter reliability.

In this paper, it is considered that the failure of one converter causes loss of load in the microgrid, and hence, the system is not reliable. Therefore, the overall system reliability can be modeled by series network reliability analysis considering the reliability of inverter, FCS and battery converter. Hence, the overall system reliability is calculated based on (8) and illustrated in Fig. 16(d).

$$\mathcal{R}_{system} = \mathcal{R}_{BT} \cdot \mathcal{R}_{FCS} \cdot \mathcal{R}_{Inv} \tag{8}$$

where R_{Inv}, R_{BT}, R_{FC} and R_{sysem} are the reliability functions of inverter, battery, and FCS converters. As it is illustrated in Fig. 16(d), the overall reliability of the grid will be improved from 46.4% to 62.7% within 15 years of operation under the proposed power sharing scheme. Furthermore, if a desired reliability level of 90% is considered, applying the proposed strategy shifts the overall system lifetime by one year.

In order to further highlight the impact of mission profile on the overall system reliability, three cases are considered with the ambient temperature being (i) equal to, (ii) 5ºC lower than, and (iii) 5ºC higher than the one shown in Fig. 5(b). The impact of cold or hot ambient temperature is illustrated in Fig. 17. As it can be seen from this figure, the proposed power sharing method improves the overall system reliability in three cases compared to the conventional approach. Furthermore, the improvement depends on the mission profiles.

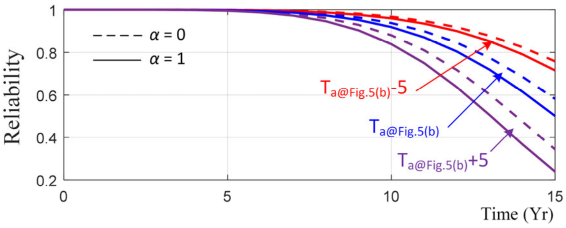

Fig. 17. Impact of ambient temperature on the overall system reliability considering the ambient temperature of 5ºC lower and 5ºC higher than the mission profile shown in Fig. 5(b) – solid-line: conventional and dashed-line: proposed method.

IV. EXPERIMENTAL VALIDATIONS

Taking into account the presented analysis, it is expected that an appropriate load sharing among converters can improve the overall system reliability. This section demonstrated the applicability of the proposed approach for reliable power sharing control in dc microgrids. In order to validate the effectiveness of the proposed approach, the impact of loading on the reliability of a bi-directional boost converter (see Fig. 4(e)) is demonstrated.

The photograph of the implemented converter setup is shown in Fig. 18. An IR thermal camera is used to measure the IGBT and diode junction temperatures. To do so, the dielectric gel of a power semiconductor module (1200V/50A) was removed to have access to the diode and IGBT wire bonds. Moreover, a customized electrolytic capacitor (490μF, 450V) with a thermal sensor is employed in this prototype to directly measure the hot-spot temperature. The implemented converter parameters are summarized in Table II. The converter is operated under four loading conditions as given Table II. The measured junction temperatures of IGBT and diode are demonstrated in Fig. 19. Also, the capacitor hot-spot temperature under given loads is shown in Fig. 20. Different components temperature is illustrated in Fig. 21 implying that the temperatures are proportionally rising by increasing the converter loading. The data given in Fig. 21 can be used to estimate the temperature of the components at other operating points.

Two load profiles as shown in Fig. 22 are employed and the component temperatures under these loading conditions are estimated according to Fig. 21. The annual accumulated damage of capacitor, IGBT and diode are calculated following (1) to (4) and based on measured temperatures. The results are

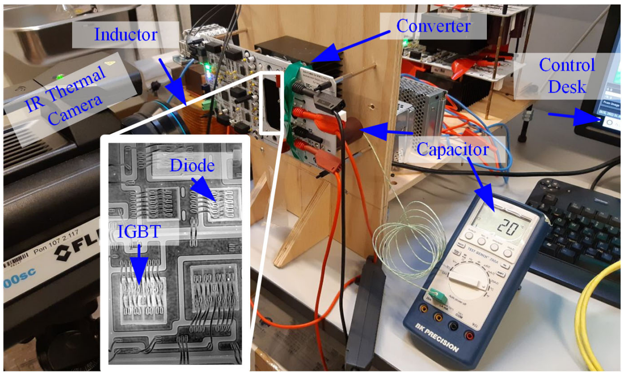

Fig. 18. Photograph of the implemented dc-dc boost converter.

Table II. Parameters of the implemented bidirectional boost converter.

Parameter	**value**
L	4 mH
C_o	490 μF
Switching Frequency	10 kHz
IGBT module	F4-50R12KS4
Input/output Voltage	210 V, 300 V
Loads	0.5, 1, 1.5, 2 kW

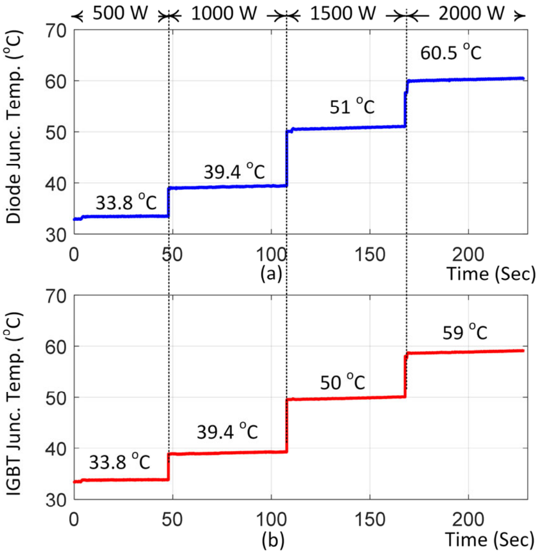

Fig. 19. Experimental results of measured junction temperature of (a) Diode and (b) IGBT under different loading conditions.

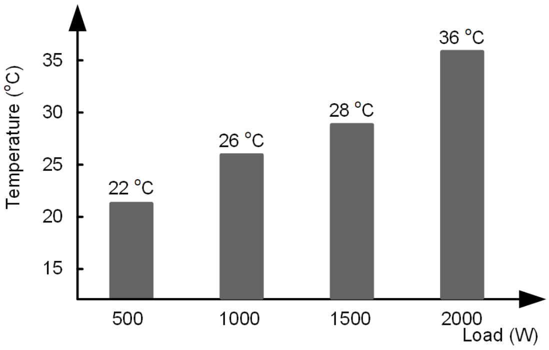

Fig. 20. Experimental results of capacitor hot-spot temperature under different loading conditions.

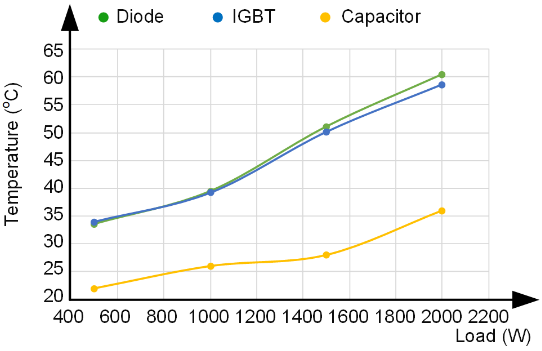

Fig. 21. Experimental results of IGBT, Diode and capacitor temperatures under different loading conditions.

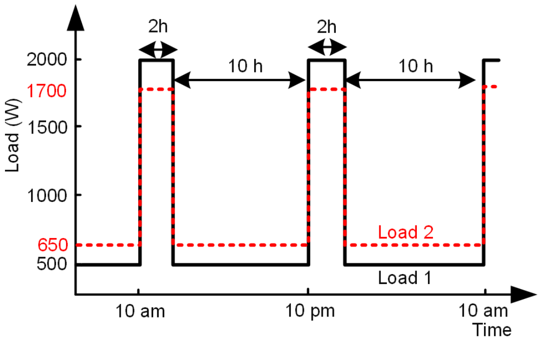

Fig. 22. Two different load profiles applied for experimental study.

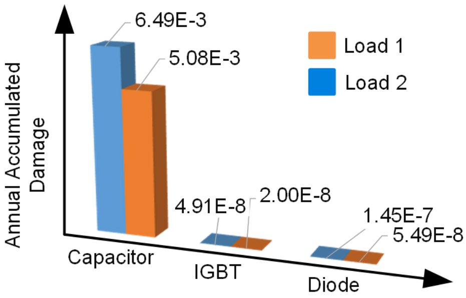

Fig. 23. Annual accumulated damage calculated based on the experimental measurements for two load profiles.

reported in Fig. 23, where the capacitor damage is significantly higher than IGBT and diode. This fact has been illustrated by the simulations as well. Furthermore, the capacitor damage employing load profile 1 is 6.49E-3 and 5.08E-3 for load profile 2. Since the converter is operated under rated power, the annual damages have small values. However, the impact of different loading conditions can be seen from the scaled-down analysis.

The obtained experimental results highlight the significant impact of loading profile on the converter lifetime, where the converter loading can change the junction temperature of semiconductors and hotspot temperature of capacitors. As a result, the lifetime of these components will be affected according to (1) and (3), and the converter reliability can be modified. By implementing a supervisory control in a multi-converter system as shown in Fig. 4, the load sharing among converters can be controlled considering their past reliability performance. Consequently, the damage and reliability of the converters will be adjusted and the overall system reliability will be improved.

V. CONCLUSIONS

This paper proposes a system-level lifetime-oriented power sharing strategy for modern power systems in order to enhance the overall system reliability. The proposed approach is applied to a dc microgrid; however, it can be generalized for any multi-converter system. According to the proposed load sharing strategy, the loading of a converter is modified inversely proportional to electro-thermal damages on its components. Therefore, the lifetime of the converters prone to premature aging is extended according to the prior experienced operating conditions. As a result, the overall system reliability can be improved.

The numerical analysis on a dc microgrid shows that the system reliability is increased from 46.4% using conventional power sharing approach to 62.7% employing the proposed scheme within 15 years of operation. Moreover, the capacitors are the dominating components on the reliability of battery and fuel cell stack converters, while diodes are the sensitive components of the inverter. Hence, the proposed strategy modifies the capacitors hot-spot temperature and diodes junction temperature by adjusting the converter loading to degrade corresponding thermal stresses. Furthermore, the proposed methodology can be generalized by including the lifetime model of any other components. Hence, any stressor impact on the converter can be recognized and mitigated/diminished by the control system. The experimental validations demonstrate the applicability of the reliability-oriented load sharing approach for dc microgrids.

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REFERENCES

[1] K. Fischer, K. Pelka, A. Bartschat, B. Tegtmeier, D. Coronado, C. Broer, and J. Wenske, "Reliability of Power Converters in Wind Turbines: Exploratory Analysis of Failure and Operating Data from a Worldwide Turbine Fleet," *IEEE Trans. Power Electron.*, vol. DOI: 10.11, no. Early Access, pp. 1–13, 2018.

[2] A. Isidori, F. M. Rossi, and F. Blaabjerg, "Thermal Loading and Reliability of 10 MW Multilevel Wind Power Converter at Different Wind Roughness Classes," in *Proc. IEEE ECCE*, 2012, pp. 2172–2179.

[3] K. Ma and F. Blaabjerg, "Modulation Methods for Neutral-Point-Clamped Wind Power Converter Achieving Loss and Thermal Redistribution Under Low-Voltage Ride-Through," *IEEE Trans. Ind. Electron.*, vol. 61, no. 2, pp. 835–845, Feb. 2014.

[4] K. Ma, M. Liserre, and F. Blaabjerg, "Reactive Power Influence on the Thermal Cycling of Multi-MW Wind Power Inverter," *IEEE Trans. Ind. Appl.*, vol. 49, no. 2, pp. 922–930, Mar. 2013.

[5] Z. Qin, M. Liserre, F. Blaabjerg, and H. Wang, "Energy Storage System by Means of Improved Thermal Performance of a 3 MW Grid Side Wind Power Converter," in *Proc. IEEE IECON*, 2013, pp. 736–742.

[6] Z. Qin, M. Liserre, F. Blaabjerg, and L. Poh Chiang, "Reliability-Oriented Energy Storage Sizing in Wind Power Systems," in *Proc. IEEE IPEC*, 2014, pp. 857–862.

[7] Y. Wu, M. A. Shafi, A. M. Knight, and R. A. McMahon, "Comparison of the Effects of Continuous and Discontinuous PWM Schemes on Power Losses of Voltage-Sourced Inverters for Induction Motor Drives," *IEEE Trans. Power Electron.*, vol. 26, no. 1, pp. 182–191, Jan. 2011.

[8] M. Andresen, G. Buticchi, and M. Liserre, "Study of Reliability-Efficiency Tradeoff of Active Thermal Control for Power Electronic Systems," *Microelectron. Reliab.*, vol. 58, pp. 119–125, Mar. 2016.

[9] H. Wang, A. M. Khambadkone, X. Yu, Huanhuan Wang, A. M. Khambadkone, X. Yu, H. Wang, A. M. Khambadkone, and X. Yu, "Control of Parallel Connected Power Converters for Low Voltage Microgrid—Part II: Dynamic Electrothermal Modeling," *IEEE Trans. Power Electron.*, vol. 25, no. 12, pp. 2971–2980, Dec. 2010.

[10] S. Peyghami, P. Davari, H. Wang, and F. Blaabjerg, "Reliability and Risk Assessment in a Power Electronic Based Power System (PEPS): Using Non-Constant Failure Rates of Converters - IEEE Conference Publication," in *Proc. IEEE ECCE EUROPE*, 2018, pp. 1–10.

[11] S. Peyghami, H. Wang, P. Davari, and F. Blaabjerg, "Mission Profile Based Power Converter Reliability Analysis in a DC Power Electronic Based Power System," in *Proc. IEEE ECCE*, 2018, pp. 1–7.

[12] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, and P. Tavner, "An Industry-Based Survey of Reliability in Power Electronic Converters," *IEEE Trans. Ind. Appl.*, vol. 47, no. 3, pp. 1441–1451, May 2011.

[13] K. Ma, Z. Qin, and D. Zhou, "Active Thermal Control for Improved Reliability of Power Electronics Systems," in *Reliability of Power Electronic Converter Systems*, Institution of Engineering and Technology, 2015, pp. 195–222.

[14] 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. Top. Power Electron.*, vol. 2, no. 1, pp. 97–114, Mar. 2014.

[15] J. Falck, C. Felgemacher, A. Rojko, M. Liserre, and P. Zacharias, "Reliability of Power Electronic Systems: An Industry Perspective," *IEEE Ind. Electron. Mag.*, vol. 12, no. 2, pp. 24–35, Jun. 2018.

[16] H. S. Chung, H. Wang, F. Blaabjerg, and M. Pecht, "*Reliability of Power Electronic Converter Systems.*" The Institution of Engineering and Technology (IET), 2016.

[17] 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.

[18] F. Blaabjerg, K. Ma, and D. Zhou, "Power Electronics and Reliability in Renewable Energy Systems," in *Proc. IEEE ISIE*, 2012, pp. 19–30.

[19] H. Wang, K. Ma, and F. Blaabjerg, "Design for Reliability of Power Electronic Systems," *IECON 2012 - 38th Annu. Conf. IEEE Ind. Electron. Soc.*, pp. 33–44, Oct. 2012.

[20] P. D. Reigosa, H. Wang, Y. Yang, F. Blaabjerg, P. D. Reigosa, H. Wang, Y. Yang, and F. Blaabjerg, "Prediction of Bond Wire Fatigue of IGBTs in a PV Inverter under a Long-Term Operation," *IEEE Trans. Power Electron.*, vol. 31, no. 10, pp. 3052–3059, Mar. 2016.

[21] S. Peyghami, P. Davari, H. Wang, and F. Blaabjerg, "System-Level Reliability Enhancement of DC/DC Stage in a Single-Phase PV Inverter," *Microelectron. Reliab.*, vol. 88–90, pp. 1030–1035, Sep. 2018.

[22] S. Peyghami, P. Davari, H. Wang, and F. Blaabjerg, "The Impact of Topology and Mission Profile on the Reliability of Boost-Type Converters in PV Applications," in *Proc. IEEE COMPEL*, 2018, pp. 1–8.

[23] S. Peyghami, H. Mokhtari, P. Davari, P. C. Loh, and F. Blaabjerg, "On Secondary Control Approaches for Voltage Regulation in DC Microgrids," *IEEE Trans. Ind. Appl.*, vol. 53, no. 5, pp. 4855–4862, Sep. 2017.

[24] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. De Vicuña, and M. Castilla, "Hierarchical Control of Droop-Controlled AC and DC Microgrids - A General Approach toward Standardization," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 158–172, 2011.

[25] S. Peyghami, P. Davari, H. Mokhtari, P. C. Loh, and F. Blaabjerg, "Synchronverter-Enabled DC Power Sharing Approach for LVDC Microgrids," *IEEE Trans. Power Electron.*, vol. 32, no. 10, pp. 8089–8099, Oct. 2017.

[26] L. Meng, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, "Tertiary and Secondary Control Levels for Efficiency Optimization and System Damping in Droop Controlled DC–DC Converters," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2615–2626, Nov. 2015.

[27] I. U. Nutkani, W. Peng, P. C. Loh, and F. Blaabjerg, "Cost-Based Droop Scheme for DC Microgrid," in *Proc. IEEE ECCE*, 2014, pp. 765–769.

[28] S. Peyghami, P. Davari, and F. Blaabjerg, "System-Level Lifetime-Oriented Power Sharing Control of Paralleled DC/DC Converters," in *Proc. IEEE APEC*, 2018, pp. 1890–1895.

[29] V. Raveendran, M. Andresen, and M. Liserre, "Improving Onboard Converter Reliability For More Electric Aircraft With Lifetime-Based Control," *IEEE Trans. Ind. Electron.*, pp. 1–10, 2019.

[30] D. Zhou, H. Wang, and F. Blaabjerg, "Mission Profile Based System-Level Reliability Analysis of DC/DC Converters for a Backup Power Application," *IEEE Trans. Power Electron.*, vol. 33, no. 9, pp. 8030–8039, 2018.

[31] R. Bayerer, T. Herrmann, T. Licht, J. Lutz, and M. Feller, "Model for Power Cycling Lifetime of IGBT Modules - Various Factors Influencing Lifetime," in *Proc. IEEE CIPS*, 2008, pp. 1–6.

[32] "Technical Information IGBT Modules Use of Power Cycling Curves for IGBT 4," Germany, 2012.

[33] A. Albertsen, "Electrolytic Capacitor Lifetime Estimation," *JIANGHAI Eur. GmbH*, pp. 1–13, 2010.

[34] A. Wintrich, N. Ulrich, T. Werner, T. Reimann, U. Nicolai, W. Tursky, and T. Reimann, "*Application Manual Power Semiconductors,*" 2nd ed. Germany: ISLE Verlag, 2015.

[35] ABB, "Application Note 5SYA 2053-04: Applying IGBTs," 2004.

[36] P. Asimakopoulos, K. D. Papastergiou, T. Thiringer, A. M. Bongiorno, and G. L. Godec, "On Vce Method: In-Situ Temperature Estimation and Aging Detection of High-Current IGBT Modules Used in Magnet Power Supplies for Particle Accelerators," *IEEE Trans. Ind. Electron.*, pp. 1–1, 2018.

[37] S. Peyghami, H. Mokhtari, and F. Blaabjerg, "Autonomous Power Management in LVDC Microgrids Based on a Superimposed Frequency

Droop," *IEEE Trans. Power Electron.*, vol. 33, no. 6, pp. 5341–5350, Jun. 2018.

[38] S. Peyghami, H. Mokhtari, and F. Blaabjerg, "Hierarchical Power Sharing Control in DC Microgrids," in *Microgrid*, First., Magdi S Mahmoud, Ed. Elsevier Science & Technology, 2017, pp. 63–100.

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