Letters

A Current Limiting Strategy for WBG-Based Solid-State Circuit Breakers With Series-Connected Switching Cells

Zhou Dong, *Student Member, IEEE*, Ching-Hsiang Yang, *Student Member, IEEE*, Shimul Kumar Dam, Dehao Qin, *Student Member, IEEE*, Ruirui Chen, *Member, IEEE*, Fei Wang, *Fellow, IEEE*, Hua Bai, *Senior Member, IEEE*, and Zheyu Zhang, *Senior Member, IEEE*

***Abstract*—The current limiting function enables the solid-state circuit breaker (SSCB) to have proper protection coordination. It allows sustained overcurrent for a certain period while preventing the fast fault current increase in dc systems. For the conventional method of using switches alone to limit the current, the high loss results in a short withstand time and low current limiting capability of the SSCBs. In this letter, a control strategy is proposed to utilize the energy absorption component to handle the major part of the energy during the current limiting stage to increase the current limiting capability for series-connected SSCB switching cells. The proposed method is experimentally verified to have more than 3X current limiting withstand time compared to the conventional control strategy in a case study.**

***Index Terms*—Fault current limiting, GaN HEMT, solid-state circuit breaker, TVS diode.**

I. Introduction

With emerging dc distributions in electrical systems, protection becomes more challenging due to the lack of zero current crossings, and fast rising fault current caused by large dc-link capacitance and low fault impedance. Solid-state circuit breakers (SSCBs) can function effectively in dc systems and also can provide fast protection. Even with their fast interruption capability, the current limiting function is often desired for SSCBs for more intelligent protection coordination in a system. It allows the SSCB to have a longer sustained time before trip and avoid the risk of a very high short circuit fault current. Moreover, it can limit the unwanted current contribution to the fault, which also mitigates voltage sags [1].

There are three common methods to embed the current limiting function to the SSCBs: adding inductors or resistors; operating in the chopper mode with freewheeling diodes; and utilizing the saturation region of switches. For the first solution, it can enable a long current limiting withstand time but is likely to be bulky and heavy, which is not suitable for applications requiring high power density [1], [2], [3]. Moreover, it could increase the conduction loss during normal operations. For the second solution, by operating the main switches in high-frequency switching mode with freewheeling diodes, the current limiting is achieved in [4] and [5]. Since the extra components added are mainly semiconductor devices with low volume and weight, this solution can feature higher power density compared to the first solution. However, the switching mode operation brings the high conducted and radiated EMI issue [6]. Moreover, when the fault happens very close to the SSCB, it causes a near-zero inductance for the chopper, which could cause a high fault current. The third solution is to utilize the saturation mode of the switch with lower gate voltage [7], [8], [9]. However, during the fault current limiting mode, the devices need to withstand high power loss and heat. Thus, the current limiting withstand time for such a solution is relatively short, especially for wide bandgap (WBG) devices.

The proposed work aims to improve the current limiting capability of the saturation-mode semiconductor device based method without compromising its advantages. The proposed method uses the energy-absorbing elements of SSCBs and is highly suitable for SSCBs with series-connected switching cells, needed to achieve sufficient voltage blocking in medium- and high-voltage applications. Compared with existing approaches, the advantages of the proposed method are as follows.

1) Current limiting time is improved by a factor of 3–4 compared to existing saturation-mode current limiting SSCB.
2) No additional hardware is needed, leading to compact implementation.

Manuscript received 28 May 2022; revised 13 July 2022; accepted 6 August 2022. Date of publication 17 August 2022; date of current version 6 September 2022. This work was supported by ARPA-E under Award DE-AR0001467 and in part by the Engineering Research Center Shared Facilities supported by the Engineering Research Center Program of the National Science Foundation and the Department of Energy under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program. *(Corresponding author: Zhou Dong.)*

Zhou Dong, Ching-Hsiang Yang, Shimul Kumar Dam, Ruirui Chen, and Hua Bai are with the Department of Electrical Engineering and Computer Science, The University of Tennessee, Knoxville, Knoxville, TN 37996 USA (e-mail: zdong9@vols.utk.edu; cyang30@vols.utk.edu; sdam@utk.edu; rchen14@vols.utk.edu; kevinbai@icloud.com).

Dehao Qin and Zheyu Zhang are with the College of Engineering Computing and Applied Sciences, Clemson University, Clemson, SC 29634 USA (e-mail: dehaoq@g.clemson.edu; zheyuz@clemson.edu).

Fei Wang is with the Department of Electrical Engineering and Computer Science, The University of Tennessee, Knoxville, Knoxville, TN 37996 USA, and also with the Oak Ridge National Laboratory, Oak Ridge, TN 37830 USA (e-mail: fred.wang@utk.edu).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TPEL.2022.3199162.

Digital Object Identifier 10.1109/TPEL.2022.3199162

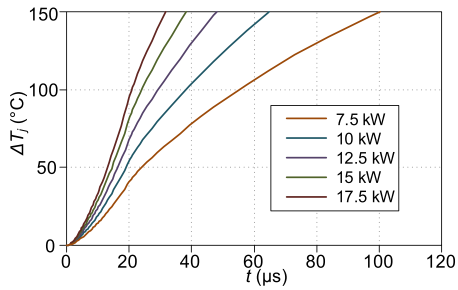


Fig. 1. Temperature rises of GS-065-150 under different loss conditions.

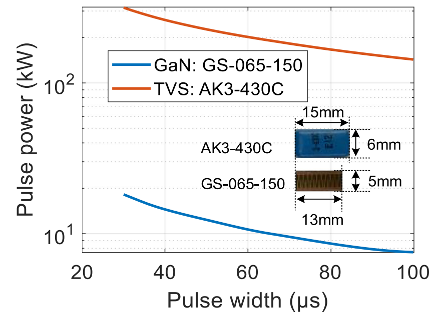


Fig. 2. Pulse power capabilities comparison between a GaN HEMT and a TVS diode.

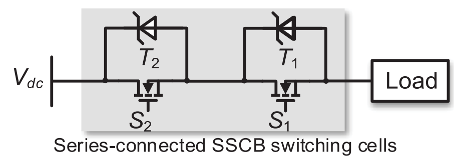


Fig. 3. Two series-connected SSCBs or SSCB switching cells.

3) Can be readily applied to existing series-connected SSCB switching cells without hardware modification.
4) Simple and easily implementable control strategy.
5) No high frequency switching and related EMI issues, and not sensitive to the fault location.

Section II discusses the challenge of using WBG devices for the current limiting. Section III introduces the proposed current limiting strategy. Section IV presents the experimental results. Finally, Section V concludes this letter.

II. Challenges of Using WBG Devices for Current Limiting

The WBG devices are attractive for SSCB applications because of their low specific on-resistance R_{on} [10]. However, it is challenging to use them for current limiting due to their weak short-circuit current handling capability. For example, GaN high electron mobility transistors (HEMTs) cannot withstand a short-circuit current for more than 3 μs [11]. For current limiting with lower gate voltage, the withstand time can be longer. As an example of GS-065-150 (650 V and 150 A rated @ $T_c = 25$ °C) from the GaN systems, the junction temperature rises under different loss conditions are shown in Fig. 1 based on the thermal impedance model provided in the official LTspice model. With 250-V and 60-A stresses (15 kW) during the current limiting stage, it only takes around 38 μs for the device junction to reach the temperature limit of 175 °C starting from an ambient temperature of 25 °C, which is insufficient for the system protection coordination. As an example, aircraft application normally requires sustaining the peak let-through current for at least 100 μs [12].

There are some dedicated energy absorption components in the SSCB, e.g., transient voltage suppression (TVS) diodes, that feature much higher pulse power and energy capability. As an example, AK3-430C from Littelfuse company has a similar package area to GS-065-150. The pulse power capabilities of the two components under different pulsewidths are compared in Fig. 2. The TVS diode has more than 10X pulse power capability and the reasons are as follows.

1) The TVS diode can have a transient maximum junction temperature of 275 °C without degradation [13], which gives a higher temperature rise margin.
2) The TVS diode can be designed much thicker for a greater mass. Also with higher specific heat, the energy required for the same temperature rise can be much greater.

On the other hand, commercial WBG devices still have limited breakdown voltage. For example, commercial GaN HEMTs are limited to 650 V nowadays. Luckily, in SSCB applications, the series connection is popular owing to the natural voltage balance with the voltage clamping by the paralleled energy absorption components [14], [15]. Moreover, the series connection would not have penalty on the conduction loss because the specific R_{on} is proportional to the square of the device breakdown voltage for the same material [10].

Therefore, the design approach depicted in the following section is to combine TVS diodes with GaN HEMTs to maximize the current limiting capability of the SSCB with series-connected switching cells.

III. Proposed Current Limiting Control Strategy

The proposed current limiting control strategy is developed for series-connected SSCB switching cells. Fig. 3 shows an example of two series-connected commonly used SSCB switching cells. The devices (S_1 and S_2) are used to open and close the SSCB, whereas the TVS diodes (T_1 and T_2) are used to absorb the inductive energy and clamp the device voltage when the SSCB opens. The idea is to utilize the high pulse power capability of TVS diodes to absorb the major part of the energy and utilize the GaN HEMT to control the limited current level. It can be achieved by operating one device in saturation mode while turning OFF the other device to break down the TVS diode to take the major part of V_{dc}. When one switch approaches its temperature limit, we can alternate to the other switch thereby fully utilizing the SSCB module.

A. Operating Principle

The proposed current-limiting control strategy of the SSCB operates in two modes, as shown in Fig. 4. In mode 1, S_2 is controlled in saturation mode by adjusting its gate voltage to

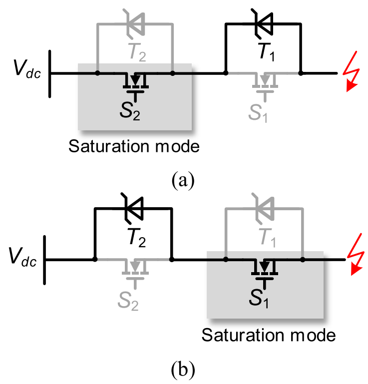


Fig. 4. Operating modes for the proposed current limiting control strategy. (a) Mode 1. (b) Mode 2.

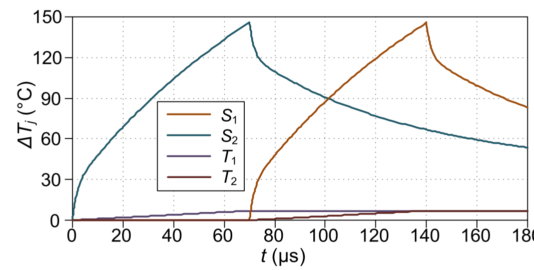


Fig. 5. Temperature rises of the components in the SSCB with the proposed current limiting control strategy.

limit the current, and S_1 is turned OFF. As explained earlier, the major part of the energy is dissipated by the TVS diode T_1 based on the voltage distribution. Then, the SSCB switches to mode 2, where S_1 is controlled in the saturation mode, and S_2 is turned OFF so that T_2 consumes the major part of the energy.

Compared to the previously used method of operating both switches S_1 and S_2 in saturation mode at the same time to limit the current, the proposed method utilizes all power components to absorb the energy by applying the two modes. Besides, with the high energy absorption capability of TVS diodes taking most of the energy, the current withstand time can be much longer than using switches alone for the same current-limiting level. Moreover, the proposed method mainly utilizes the control scheme to increase the current limiting capability of the dc SSCB without any extra hardware.

B. Selection of TVS Diodes

For SSCB applications, the overall clamping voltage of the TVS diodes needs to be higher than V_{dc} to extinguish the fault current when the switches turn OFF. Thus, the clamping voltage of one TVS diode V_{cl} should be higher than $V_{\mathrm{dc}}/2$. This is the reason why TVS diodes dissipate more energy than semiconductor devices in the proposed control approach. Specifically, for the proposed control strategy, to make the TVS diode break down in each mode, V_{cl} should be lower than V_{dc}. Otherwise, the current would keep decreasing during the current limiting period because of the higher clamping voltage than V_{dc}. Therefore, V_{cl} is recommended to be between $V_{\mathrm{dc}}/2$ and V_{dc}. The closer to V_{dc}, the more energy is taken by TVS diode and vice versa. The energy dissipated in each TVS diode is approximately $V_{\mathrm{cl}}I_{\mathrm{cl}}t_{\mathrm{cl}}$, which also needs to be considered when selecting TVS diodes. I_{cl} is the limited current level and t_{cl} is the maximum current limiting time.

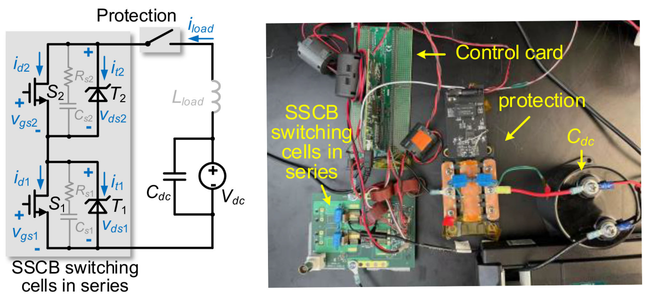
C. Coordination of Switches

The coordination of the two switches is not a concern as long as the timing mismatch is controlled within tens of nanosecond. There are two kinds of mismatches. First, two switches have some overlapped turn-ON time. In this short transition, both switches will be in the current limiting mode, which is the same as the conventional approach. Moreover, since this overlap time can easily be controlled to be short, the energy dissipation can be ignored compared to the whole current limiting period. Second, if two switches have some overlapped turn-OFF time, then the fault current will go through TVS diodes due to the loop inductance. The breakdown voltage of two series TVS diodes is higher than the input voltage, which helps to reduce the fault current. This is also acceptable considering the short overlap time.

D. Case Study

A system with 500-V V_{dc} and two SSCB switching cells is considered, where S_1 and S_2 are GaN HEMTs GS-065-150, and T_1 and T_2 are TVS diodes AK3-430C. Using two GaN HEMTs in series for the current limiting of 60 A results in 250-V voltage stress and 15-kW transient power loss in each device. The withstand time is 38 μs based on Fig. 1 assuming balanced voltage distribution. With the proposed current limiting control strategy, the TVS diode takes around 350 V so that each GaN HEMT only has 150-V voltage stress and 9-kW power loss. The withstand time can be 70 μs for each mode and 140 μs for both two modes, which is ~3.7X of the conventional method. For the TVS diode, the loss is 27 kW, which is much less than the pulse power capability (184 kW) for a 70-μs pulsewidth. The extra pulse power capability can still be used to absorb the loop inductance energy when the SSCB opens. The junction temperature rises for GaN HEMTs and TVS diodes using the proposed control strategy are simulated and shown in Fig. 5. The GaN HEMTs approach the temperature limit while the TVS diodes have a limited temperature rise (<10 °C) compared to the GaN HEMTs. Although the dynamic thermal impedance model could have some inaccuracies in the simulation, it is still a fair comparison when both conventional and proposed methods use the same model to estimate the junction temperature and current limiting capability.

This current limiting function with microsecond range period can give a delay to the short-circuit protection to suppress the effect of noise as applied in [16]. On the other hand, for some applications, the current limiting withstand time could be as long as millisecond range to coordinate with other breakers, paralleling of the devices can be applied. A similar analysis or simulation can be implemented to select the device and the parallel number to ensure that the device junction temperature can be limited within the maximum value. In any case, the proposed control strategy requires a lower current rating device



(a) (b)

Fig. 6. Test circuit and platform of the SSCB. (a) Test circuit. (b) Test platform.

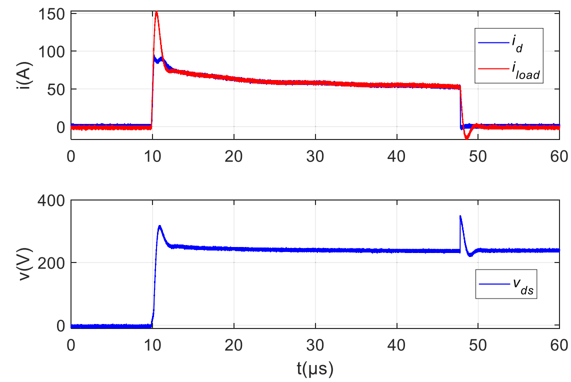


Fig. 7. Test waveforms of the conventional current limiting strategy.

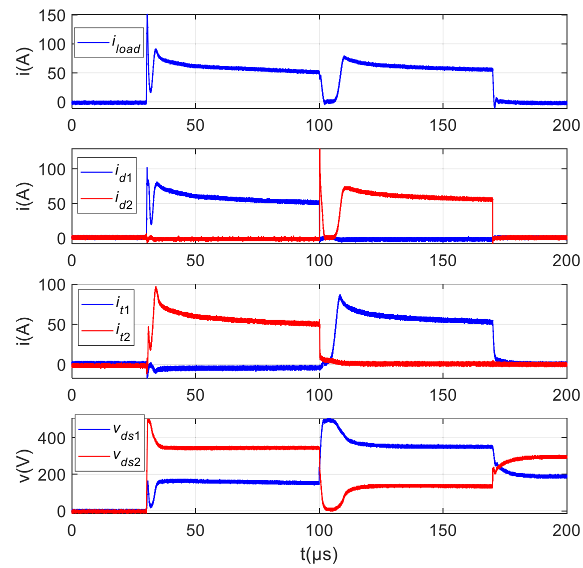


Fig. 8. Test waveforms of the proposed current limiting strategy w/o load inductance.

or less paralleling compared to the conventional method because the required energy dissipation for the GaN HEMTs is smaller.

IV. Experimental Results

The proposed current limiting strategy is experimentally verified in this section and compared with the conventional approach to verify the benefits. The rated voltage for the test is set as 500 V and the limited current level is around 60 A. Note that since the main objective of the experiment is to verify the current limiting capability of the proposed control strategy, only the open loop control is implemented. For the closed-loop control, the proposed approach can follow the conventional approach in [16].

A. Test Circuit and Platform

The test circuit and platform are shown in Fig. 6. It includes two series-connected SSCB switching cells. Each switching cell has one GaN HEMT GS-065-150 and one TVS diode AK3-430C. The series of two switching cells are needed to make sure the overall clamping voltage is higher than V_{dc} to ensure that the SSCB can interrupt the fault current, which is valid for cases with both conventional and proposed current limiting control strategy. Besides, an *RC* snubber, which is optional, is paralleled with each switching cell to suppress the overvoltage during turn-OFF. The *RC* snubber design follows the analysis in [17] to minimize the voltage spike during turn-OFF. The designed values are 150 nF for capacitance and 0.5 Ω for resistance. A load inductance L_{load} is optional for emulating the fault conditions with cable inductance in the loop. A protection switch is also applied to protect the devices under test.

B. Test Results of Conventional Current Limiting Strategy

For the conventional current limiting strategy, both GaN HEMTs are in saturation mode to limit the fault current. The voltage across the two switches needs to be balanced for the optimal operating condition. To simplify the test, only one GaN HEMT is used in the test with half of the rated dc input voltage. The gate-to-source voltage is set at around 1.8 V to limit the current to around 60 A. Fig. 7 shows the test waveforms, which are for the condition without load inductance. The voltage is measured by the differential probe TMDP0200 from Tektronix, and the current is measured by the Rogowski coil CWT3 from PEM. The device successfully limits the current at around 60 A with 250-V voltage stress for 38 μs, which is the maximum current limiting withstand time from the thermal simulation model. Note that there are overshoots of both voltage and current at the beginning of the current limiting, which is because the device has a lower junction temperature at the beginning of the current limiting period. The GaN HEMT has a higher saturation current with a lower junction temperature under the same gate-to-source voltage condition. This current variation is acceptable for the SSCB reaction to a system with potential faults. Compared to i_d, i_{load} has a current spike at the beginning of the current limiting, which is because extra current is needed to charge the device output capacitance and the capacitor of the *RC* snubber.

C. Test Results of Proposed Current Limiting Strategy

The test waveforms of the proposed current-limiting strategy are shown in Figs. 8 and 9. In Fig. 8, the proposed current limiting strategy is tested without load inductance. Similar to the test results in Fig. 7, the load current decreases after the junction temperature of each device increases. For measured v_{ds1} and

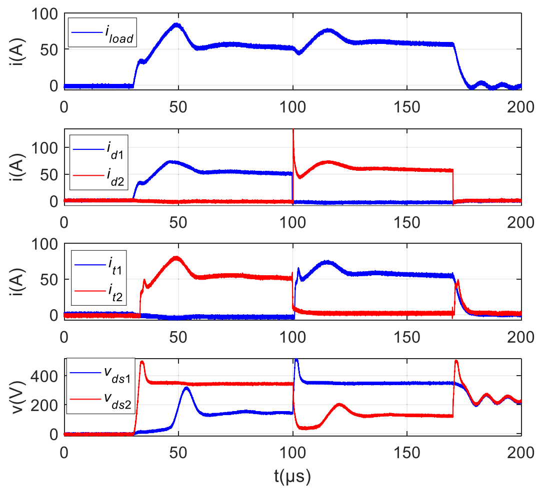


Fig. 9. Test waveforms of the proposed current limiting strategy w/ 38 μH load inductance.

TABLE I
COMPARISON OF ENERGY DISSIPATED USING DIFFERENT METHODS

Methods	Energy generated and dissipated (J)				Withstand time (μs)
	S_1	S_2	T_1	T_2	
Conventional	0.56	0.56*	0	0	38
Proposed (no load inductance)	0.57	0.47	1.36	1.38	140
Proposed (38 μH load inductance)	0.42	0.49	1.46	1.39	140

*Assume S_2 has the same energy generated as S_1

v_{ds2}, a higher voltage can be observed at the beginning of the TVS breakdown. This phenomenon is called "foldback," which is a special characteristic of the high power TVS diode to provide a lower clamping voltage than the avalanche to withstand high fault current within a small package [14]. Note that when S_2 turns ON at $t = 100$ μs, the load current decreases to around zero due to this high TVS breakdown voltage and the near-zero load inductance. This is acceptable for a system with potential fault while the SSCB keeps the current limiting status with devices not being fully turned OFF.

In Fig. 9, the proposed current limiting strategy is tested with a load inductance of 38 μH. With higher load inductance, the load current varies smoothly and is successfully limited for 140 μs, which is the maximum current limiting withstand time from the thermal simulation model. For both tests of the proposed current limiting strategy, the gate-to-source voltage is the same as the conventional case of 1.8 V to have a similar limited current level for a fair comparison.

D. Results Comparison

The energies dissipated in each component and the current limiting withstand time of the two methods are compared in Table I. Using the proposed current limiting strategy, with a similar GaN HEMT energy dissipation, the short-circuit withstand time can be increased from 38 to 140 μs (3.7X) without adding extra hardware. Also, TVS diodes are verified to generate and absorb a major part of the energy in the proposed control strategy.

V. Conclusion

In this letter, we proposed a novel current limiting control strategy for series-connected SSCB switching cells. The current limiting function is enhanced by utilizing the higher robustness and energy absorption capability of TVS diodes and alternating two GaN switches. Besides, no extra hardware is needed. The proposed strategy is verified to have a longer current limiting withstand time of 140 μs ($\sim$3.7X of the conventional method of 38 μs) without requiring extra hardware. Moreover, for only two SSCB switching cells in series, no voltage balancing is needed for the current limiting period. In the future, the proposed control strategy can be extended to cases with more than two SSCB switching cells in series.

References

[1] A. Abramovitz and K. M. Smedley, "Survey of solid-state fault current limiters," *IEEE Trans. Power Electron.*, vol. 27, no. 6, pp. 2770–2782, Jun. 2012.

[2] B. Li, J. He, Y. Li, and R. Li, "A novel solid-state circuit breaker with self-adapt fault current limiting capability for LVDC distribution network," *IEEE Trans. Power Electron.*, vol. 34, no. 4, pp. 3516–3529, Apr. 2019.

[3] F. Luo, J. Chen, X. Lin, Y. Kang, and S. Duan, "A novel solid state fault current limiter for DC power distribution network," in *Proc. 23rd Annu. IEEE Appl. Power Electron. Conf. Expo.*, 2008, pp. 1284–1289.

[4] M. M. R. Ahmed, G. Putrus, L. Ran, and R. Penlington, "Development of a prototype solid-state fault-current limiting and interrupting device for low-voltage distribution networks," *IEEE Trans. Power Del.*, vol. 21, no. 4, pp. 1997–2005, Oct. 2006.

[5] Y. Zhou, Y. Feng, T. Liu, and Z. J. Shen, "Short circuit fault location in DC power network using intelligent SiC solid-state circuit breaker," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2018, pp. 485–491.

[6] M. M. R. Ahmed, G. A. Putrus, L. Ran, and L. Xiao, "Harmonic analysis and improvement of a new solid-state fault current limiter," *IEEE Trans. Ind. Appl.*, vol. 40, no. 4, pp. 1012–1019, Jul./Aug. 2004.

[7] M. Komatsu, "Approach and basic evaluation for the DC circuit breaker with fault current limiting feature," in *Proc. IEEE Int. Telecommun. Energy Conf.*, 2016, pp. 1–5.

[8] D. Marroquí, J. M. Blanes, A. Garrigós, and R. Gutiérrez, "Self-powered 380 V DC SiC solid-state circuit breaker and fault current limiter," *IEEE Trans. Power Electron.*, vol. 34, no. 10, pp. 9600–9608, Oct. 2019.

[9] K. Tan, X. Song, C. Peng, P. Liu, and A. Q. Huang, "Hierarchical protection architecture for 380V DC data center application," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2016, pp. 1–8.

[10] J. Everts, J. Das, J. Van dan Keybus, M. Germain, and J. Driesen, "GaN-based power transistors for future power electronic converters," in *Proc. IEEE Benelux Young Res. Symp.*, 2010, pp. 1–6.

[11] N. Badawi, A. E. Awwad, and S. Dieckerhoff, "Robustness in short-circuit mode: Benchmarking of 600V GaN HEMTs with power Si and SiC MOSFETs," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2016, pp. 1–7.

[12] AS4805-General Standard for SSPC, SAE Aerospace Standard, 2007.

[13] Microsemi Application Note, "Derating silicon transient voltage suppressor at elevated temperatures," 2018. [Online]. Available: https://www.microsemi.com/document-portal/doc_download/14610-micronote-114-derating-tvs-devices-for-higher-junction-temp

[14] Z. Dong, R. Ren, and F. Wang, "Development of high-power bidirectional DC solid-state power controller for aircraft applications," *IEEE J. Emerg. Sel. Topics Power Electron.*, early access, Dec. 31, 2021.

[15] Z. Dongye, Y. Wang, H. Zhang, S. Zheng, X. Lu, and F. Lu, "A 4kV/100A SiC MOSFETs-based solid state DC circuit breaker with low stray inductances and powered by a load-independent wireless power transfer system," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2020, pp. 1279–1283.

[16] S. Mohsenzade, M. Zarghani, and S. Kaboli, "A voltage balancing method for series-connected IGBTs operating as a fault current limiter in high-voltage DC power supplies," *IEEE Trans. Ind. Electron.*, vol. 68, no. 9, pp. 7895–7907, Sep. 2021.

[17] Y. Wu, Q. Yi, Y. Wu, F. Yang, Z. Zhang, and J. Wen, "Research on snubber circuits for power electronic switch in DC current breaking," in *Proc. 14th IEEE Conf. Ind. Electron. Appl.*, 2019, pp. 2082–2086.