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Solid-State Circuit Breaker with Avalanche Robustness using Series-Connection of SiC Diodes

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***Abstract*—This paper proposes a solid-state circuit breaker with avalanche robustness during cutoff operation using series-connection of SiC diodes. Solid-state circuit breakers need to consume energy generated by energy dissipation in the wiring inductance when the cutoff operation. The proposed solid-state circuit breaker improves the cutoff current tolerance by using SiC diodes connected in series to share the avalanche energy. Furthermore, the consuming energy by the solid-state circuit breaker is reduced by maintaining a higher clamping voltage than using single SiC diode during the interruption operation. Experimental results show that the proposed solid-state circuit breaker with two series-connection SiC diodes reduces the consumed avalanche energy by 34.3% compared to using single SiC diode under the same cutoff condition. The proposed solid-state circuit breaker is investigated based on a 400 VDC distribution system with unclamped inductive switching (UIS) condition up to 50 A cutoff current.**

***Index Terms*—avalanche robustness, silicon carbide, solid-state circuit breaker, unclamped inductive switching**

I. Introduction

DC power distribution systems are one of the key technologies supporting future power distribution systems [1]–[3]. It has been pointed out that, it is difficult for mechanical circuit breakers to cope with the DC current cutoff operations, due to interrupting speed and repetitive interruption operations. For these reasons, solid-state circuit breakers are the most promising candidate for safety equipment in low-voltage DC systems including automotive applications and electric aircrafts [4]–[8].

The circuit breakers must consume the inductive energy contained in the wiring inductance during the current cutoff operations. During this period, solid-state circuit breakers face avalanche operation with instantaneous surge voltage under unclamped inductive switching (UIS) conditions [9]. Therefore, the realization of solid-state circuit breakers has the challenge that the avalanche tolerance must be guaranteed in the power semiconductor device. Especially, silicon carbide (SiC) power semiconductor devices have superior characteristics against single and repeated avalanche operations compared to silicon (Si) power semiconductor devices [10]. Furthermore, SiC MOSFETs have superior on-resistance compared to existing Si power semiconductor devices, which can reduce conduction losses [11]. Therefore, they are one of the suitable candidates for use in solid-state circuit breaker applications.

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However, SiC MOSFETs have been pointed out to have deteriorated electrical characteristics due to fatigue of the gate oxide in the face of repeated avalanche operation [12], [13]. Therefore, it is necessary to reduce the avalanche stress on the MOSFET. For that reason, it is effective to connect a clamped element in parallel with the MOSFET to divert the current during cutoff operation.

Metal oxide varistor (MOV) and R-C snubber circuit are often connected in parallel to switching devices as used for clamped elements to reduce stress on the devices [14]–[16]. Here, the clamped elements have a lower breakdown voltage than the power semiconductor device. This design serves to divert the cutoff current and consumed the avalanche energy. Similarly, the breakdown characteristics of the diode devices act steeply with respect to the breakdown voltage. Therefore, the surge voltage at the breakdown is tightly clamped to the breakdown voltage of the device [17]. Moreover, the SiC power semiconductor devices have sufficient avalanche tolerance during current interruption operation, allowing those components to be substituted. In order to improve the avalanche tolerance of the solid-state circuit breaker, the series-connection of clamping diodes is one of the effective means.

This paper proposes a solid-state circuit breaker with high-avalanche tolerance by SiC diodes connected in series. The proposed solid-state circuit breaker improves the avalanche tolerance by using two series-connected SiC diodes. Furthermore, the energy borne by the solid-state circuit breaker is reduced by maintaining a high clamping voltage during the interruption operation of the solid-state circuit breaker. Experimental results show that the proposed solid-state circuit breaker achieves the reduction of the cutoff energy and higher avalanche capability based on 400 VDC distribution systems.

II. Unclamped Inductive Switching Condition

Fig. 1 shows schematics of the UIS test. For investigation with the same condition as the DC distribution system, the UIS test circuit is a good circuit configuration for evaluating the avalanche breakdown phenomenon in the solid-state circuit breaker. The UIS test circuit consistents of an input voltage $V_{\rm DC}$, a DC capacitance $C_{\rm DC}$, an inductance L, and a device under the test (DUT) such as a MOSFET Q.

During steady-state, a gate–source voltage $v_{\rm gs}$ remains on-state. The drain current $i_{\rm MOS}$ is equivalent to the inductance current $i_{\rm L}$. The drain current $i_{\rm MOS}$ is designed to flow at a maximum inductance current $I_{\rm L}$.

The breaking operation starts, then the gate–source voltage $v_{\rm gs}$ turns off. Because of the avalanche breakdown, the drain-source voltage $v_{\rm ds}$ reaches the breakdown voltage $V_{\rm BD(M)}$ beyond the rated voltage $V_{\rm DSS(M)}$. After that, the avalanche energy $E_{\rm AV}$ of the inductance L affects the power semiconductor device. The avalanche energy $E_{\rm AV}$ is given by

$$E_{\rm AV} = \frac{1}{2}L{I_{\rm L}}^2\frac{V_{\rm BD(M)}}{V_{\rm BD(M)} - V_{\rm DC}}, \tag{1}$$

$$= \int_{t_1}^{t_2} p_{\rm MOS}\,(t)\,{\rm d}t, \tag{2}$$

where $p_{\rm MOS}$ is defined as the dissipated power of the MOSFET Q.

After the avalanche energy $E_{\rm AV}$ in the power devices has been completely consumed, the cutoff current $i_{\rm L}$ converges to zero and the interrupting operation is complete. In the case of the solid-state circuit breaker, all the avalanche energy $E_{\rm AV}$ generated during interruption is consumed by the power semiconductor devices.

Due to SiC MOSFETs facing repeated avalanche operations, it has been reported that SiC MOSFETs undergo the gate oxide degradation occurs [12]. The gate oxide degradation causes the fluctuation of the device characteristics and affects the long-term reliability of the solid-state circuit breaker. Moreover, the current balance between parallel-connected devices during avalanche operation depends on a few electrical characteristics. To apply to circuit breakers with SiC power semiconductor devices, those issues need to be addressed.

III. Clamping Method using a Diode with Avalanche Operation

Fig. 2 shows a solid-state circuit breaker with a clamped diode. This circuit configuration provides good functionality for circuit breakers with two operations; steady-state operation and cutoff operation.

During steady-state operation, the MOSFET Q is in the on-state and all current conduct is through the MOSFET Q. On the other hand, the circuit breaker enforces the breaking operation, the current flowing through the MOSFET Q side $i_{\rm MOS}$ is diverted to the clamped diode side $i_{\rm Clamp}$ and clamped by the avalanche voltage $V_{\rm BD(D)}$. Here, the relationship between the breakdown voltage of the MOSFET Q $V_{\rm BD(M)}$ and the diode $V_{\rm BD(D)}$ is represented as follows:

$$V_{\rm DC} < V_{\rm BD(D)} < V_{\rm BD(M)} \tag{3}$$

The solid-state circuit breaker performs a current interrupting operation by having the clamped element consume the

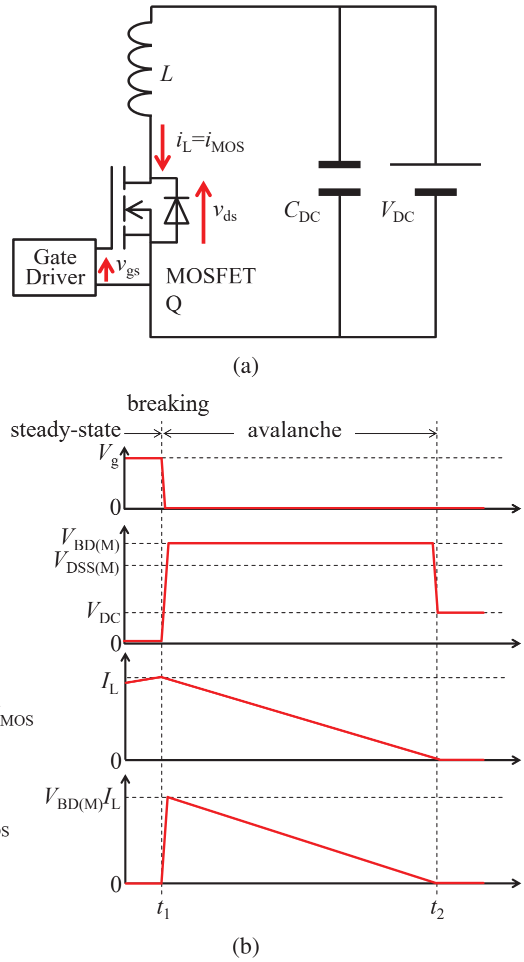

Fig. 1. UIS test. (a) circuit configuration and (b) ideal waveforms.

avalanche energy at the cutoff operation. The avalanche energy $E_{\rm AV}$ is determined as follows:

$$E_{\rm AV} = \frac{1}{2}L{I_{\rm L}}^2\frac{V_{\rm BD(D)}}{V_{\rm BD(D)} - V_{\rm DC}} \tag{4}$$

The elapsed time from start to completion of current cutoff operation $T_{\rm AV(single)}$ is given by

$$T_{\rm AV(single)} = \frac{I_{\rm L}L}{V_{\rm BD(D)} - V_{\rm DC}}. \tag{5}$$

Thus, the solid-state circuit breaker with a clamped diode is effective in reducing the avalanche stress on the MOSFET. Furthermore, they are also effective in preventing current imbalance when MOSFETs are connected in parallel to reduce the steady-state loss [17].

IV. Proposed Solid-State Circuit Breaker with Series Connection of SiC Diodes

Fig. 3 shows the proposed solid-state circuit breaker with clamped series-connection of diodes. Here, the breaker voltage $v_{\rm breaker}$ at the avalanche period is the same as the breakdown voltage of the clamped diodes. Therefore, in case of use for

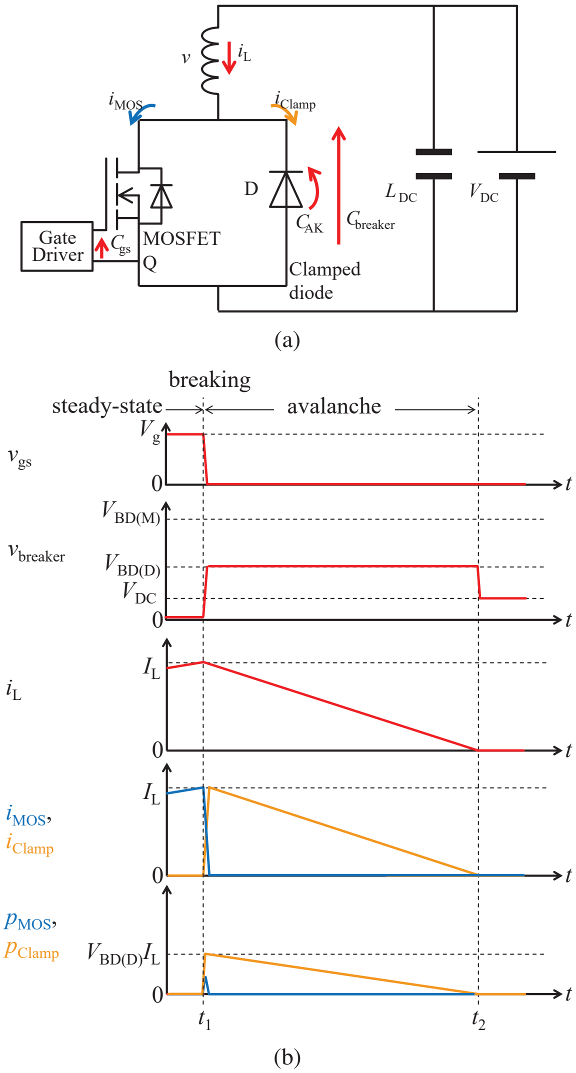

Fig. 2. A Solid-state circuit breaker with clamped a diode. (a) circuit configuration and (b) waveforms.

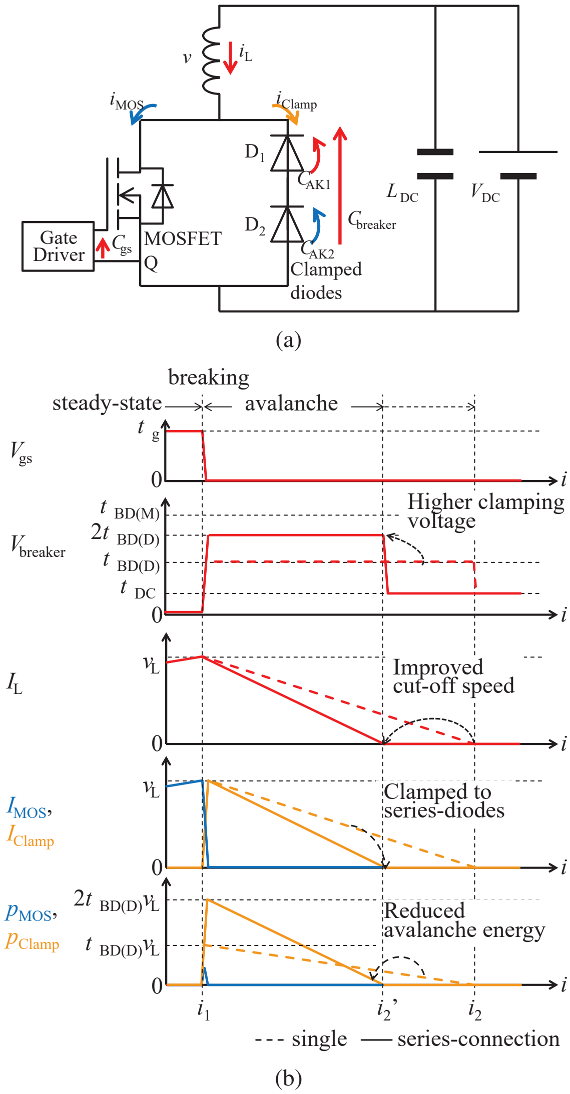

Fig. 3. Proposed solid-state circuit breaker with clamped SiC diodes in series-connection. (a) circuit configuration and (b) waveforms.

the clamped diodes with two devices in series-connection, the breaker voltage $V_{\mathrm{breaker(series)}} = 2V_{\mathrm{BD(D)}}$.

Thus, the avalanche energy $E_{\mathrm{AV(series)}}$ with connected in two series diodes is calculated as

$$E_{\mathrm{AV(series)}} = \frac{1}{2} L I_{\mathrm{L}}{}^{2} \frac{2V_{\mathrm{BD(D)}}}{2V_{\mathrm{BD(D)}} - V_{\mathrm{DC}}}, \tag{6}$$

where

$$V_{\mathrm{DC}} < 2V_{\mathrm{BD(D)}} < V_{\mathrm{BD(M)}}. \tag{7}$$

Besides, the period from start to completion of current interrupt $T_{\mathrm{AV(series)}}$ is given by

$$T_{\mathrm{AV(series)}} = \frac{I_{\mathrm{L}} L}{2V_{\mathrm{BD(D)}} - V_{\mathrm{DC}}}. \tag{8}$$

Therefore, the higher breakdown voltage of the clamped diode improve the cutoff current tolerance of the solid-state circuit breaker. Thereby completing the faster cutoff operation while the power semiconductor device maintains the lower junction temperature. Furthermore, the series-connection of SiC diodes improves the avalanche tolerance of the solid-state circuit breaker two times.

V. Experimental Result

Fig. 4 shows a picture of the solid-state circuit breaker prototype. The circuit configuration of the prototype is the same as Fig. 2(a) and Fig. 3(a). The circuit parameters are $V_{\mathrm{DC}} = 400\,\mathrm{V}$, an air-core inductance $L = 300\,\mu\mathrm{H}$. The solid-state circuit breaker consists of a MOSFET Q, and single diode D or two SiC diodes D_1, D_2 connected in series are used. For voltage balancing during the steady-state, $100\,\mathrm{k}\Omega$ balancing resistors are connected in parallel with each diode.

Table I shows the device characteristics based on datasheets and table II shows the measurement results of the devices. The measurement results were obtained using the semiconductor curve tracer (Iwatsu CS-3200). The MOSFET Q is rated at 1.7 kV (Microsemi MSC035SMA170B4), which is measured

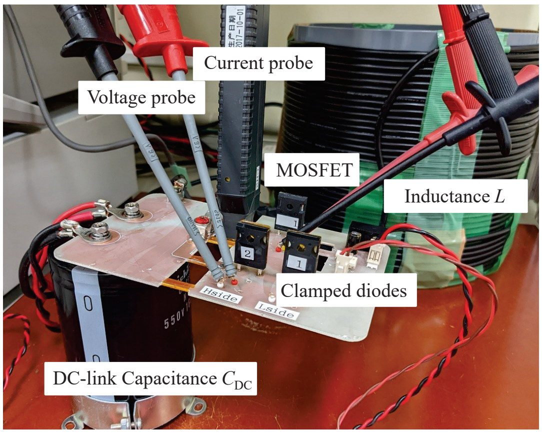

Fig. 4. Prototype of the solid-state circuit breaker.

TABLE I
DEVICE CHARACTERISTICS BASED ON DATASHEETS

Device		V_{BD}	I_D, I_F	E_{AV}
SiC MOSFET	Q	1700 V	68 A	—
SiC diode	D	650 V	40 A	182 mJ

TABLE II
MEASUREMENT RESULTS OF THE DEVICE CHARACTERISTICS

Group	Device		V_{BD}
—	MOSFET	Q	1883 V
Sigle	Diode	D	792.4 V
Series	Diode	D_1	793.7 V
	Diode	D_2	794.8 V

the breakdown voltage $V_{BD(M)} = 1883$ V. SiC diodes D, D_1 and D_2 are rated at 650 V, avalanche energy rated at 182 mJ (Onsemi FFSH4065A), whose measured breakdown voltage $V_{BD(D)}$ are 792.4 V, 793.7 V, and 794.8 V. The cutoff current I_L is measured every 5 A from $I_L = 10$ A to 50 A.

Fig. 5 shows the experimental results of the circuit breaker using single and two series-connected SiC diode as voltage clamping at cutoff current $I_L = 30$ A and table III shows a comparison of the avalanche energy. Regarding using single diode, it is observed that the breaker voltage $V_{breaker}$ is clamped by the diode breakdown voltage $V_{BD(D)}$. The breaker voltage $v_{breaker}$ is equal to the diode anode–cathode voltage v_{AK}. The cutoff operation was completed 19 µs after the initiation. The avalanche energy $E_{AV(single)} = 233$ mJ is observed.

On the other hand, for the two series-connected cases, the breaker voltage $v_{breaker}$ is clamped by the breakdown voltage $V_{BD(D)}$ of the two diodes to operate the breaker. That is, the breaker voltage $v_{breaker} = v_{AK1} + v_{AK2}$. The breaking operation was completed 7 µs after the start. The avalanche energy $E_{AV(series)} = 153$ mJ is observed. In other words, the series connection of the diodes reduced the E_{AV} consumed by the circuit breaker by 34.3%. In other words, by designing a higher clamping voltage, the E_{AV} consumed by the clamped device was reduced and the avalanche capability of the circuit breaker was improved.

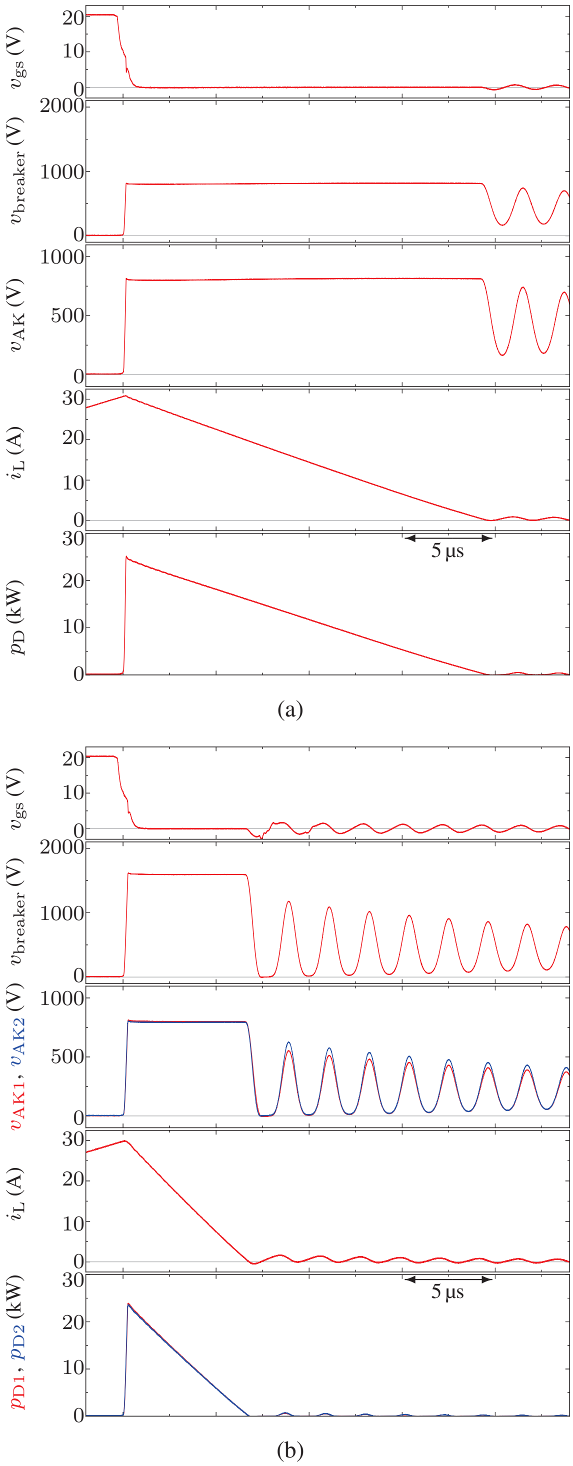

Fig. 5. Observed waveforms of cutoff operation at $I_L = 30$ A in case of (a) single diode and (b) two series-connected diodes.

Fig. 6 shows the experimental results of the solid-state circuit breaker with single and two series-connection of SiC diodes up to cutoff current $I_L = 50$ A. The solid-state circuit breaker clamped with single SiC diode survived up to 45 A cutoff current. On the other hand, diodes connected in series

TABLE III
COMPARISON OF THE AVALANCHE ENERGY E_{AV}

Method	Cutoff current I_L	Device	E_{AV}
Single	30 A	D	233 mJ
Series	30 A	D_1	76.3 mJ
		D_2	76.7 mJ

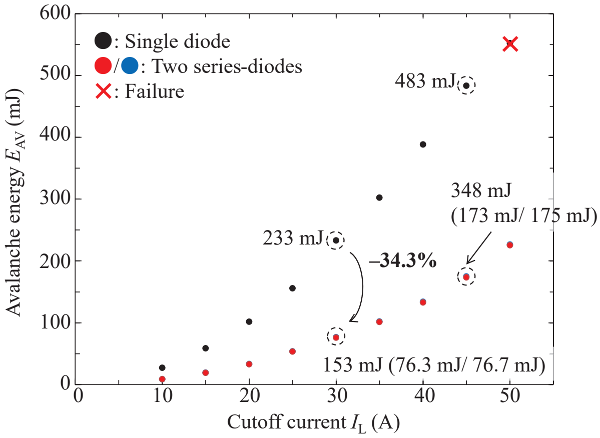

Fig. 6. Experimental results of the solid-state circuit breaker with single and two series-connection of SiC diodes.

contribute to the improvement of breaking current with the solid-state circuit breaker.

VI. CONCLUSION

This paper proposed the solid-state circuit breaker with avalanche robustness using SiC diodes connected in series. The proposed solid-state circuit breaker improved the avalanche capability using multiple SiC diodes to consume the energy generated during the current interruption. Furthermore, the energy was consumed by the solid-state circuit breaker during current interruption reduced by maintaining a higher clamped voltage of the series-connected diodes. Experimental results show that the proposed method reduces the consumed avalanche energy by 34.3% compared to single device case based on a 400 VDC distribution system up to 50 A cutoff current. The proposed method is a good candidate to improve the avalanche capability for solid-state circuit breakers.

REFERENCES

[1] I. Aghabali, J. Bauman, P. J. Kollmeyer, Y. Wang, B. Bilgin and A. Emadi, "800-V Electric Vehicle Powertrains: Review and Analysis of Benefits, Challenges, and Future Trends," in *IEEE Transactions on Transportation Electrification*, vol. 7, no. 3, pp. 927-948, Sept. 2021.

[2] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, "DC microgrids—Part II: A review of power architectures, applications, and standardization issues," in *IEEE Transactions on Power Electronics*, vol. 31, no. 5, pp. 3528-3549, May 2016.

[3] M. Okamura and T. Takaoka, "The Evolution of Electric Components in Prius," *IEEJ Journal of Industry Applications*, vol. 11, issue 1, pp. 1-6, 2022.

[4] R. Rodrigues, Y. Du, A. Antoniazzi, and P. Cairoli, "A review of solid-state circuit breakers," *IEEE Trans. Power Electron.,* vol. 36, no. 1, pp. 364–377, Jan. 2021.

[5] A. Barzkar and M. Ghassemi, "Components of Electrical Power Systems in More and All-Electric Aircraft: A Review," in *IEEE Transactions on Transportation Electrification*, vol. 8, no. 4, pp. 4037-4053, Dec. 2022.

[6] Y. Sato, Y. Tanaka, A. Fukui, M. Yamasaki, and H. Ohashi, "SiC-SIT Circuit Breakers With Controllable Interruption Voltage for 400-V DC Distribution Systems," in *IEEE Transactions on Power Electronics*, vol. 29, no. 5, pp. 2597-2605, May 2014.

[7] N. Boettcher and T. Erlbacher, "A Monolithically Integrated SiC Circuit Breaker," in *IEEE Electron Device Letters*, vol. 42, no. 10, pp. 1516-1519, Oct. 2021.

[8] T. Takamori, K. Wada, W. Saito, and S. -i. Nishizawa,"Gate drive circuit for current balancing of parallel-connected SiC-JFETs under avalanche mode," *Microelectron Reliab.*, vol. 114, Art. no. 113776, 2020.

[9] Renesas Electronics Corp., Application Note – AN1968: Unclamped Inductive Switching (UIS) Test and Rating Methodology, [Online]. Available: https://www.renesas.com

[10] X. She, A. Q. Huang, Ó. Lucía, and B. Ozpineci, "Review of silicon carbide power devices and their applications," in *IEEE Transactions on Industrial Electronics,* vol. 64, no. 10, pp. 8193-8205, Oct. 2017.

[11] K. Sato, H. Kato, and T. Fukushima, "Outstanding Technical Features of Traction System in N700S Shinkansen New Generation Standardized High Speed Train," *IEEJ Journal of Industry Applications*, vol.10, no.4, pp. 402–410, 2021.

[12] X. Deng *et al.*, "Investigation of Failure Mechanisms of 1200 V Rated Trench SiC MOSFETs Under Repetitive Avalanche Stress," in *IEEE Transactions on Power Electronics*, vol. 37, no. 9, pp. 10562-10571, Sept. 2022.

[13] J. Wei, S. Liu, S. Li, J. Fang, T. Li, and W. Sun, "Comprehensive Investigations on Degradations of Dynamic Characteristics for SiC Power MOSFETs Under Repetitive Avalanche Shocks," in *IEEE Transactions on Power Electronics*, vol. 34, no. 3, pp. 2748-2757, March 2019.

[14] G. E. Mejia-Ruiz, M. R. A. Paternina, A. Zamora-Mendez, J. C. Rosas-Caro and G. Bolivar-Ortiz, "A Novel GaN-Based Solid-State Circuit Breaker With Voltage Overshoot Suppression," in *IEEE Transactions on Industrial Electronics*, vol. 69, no. 9, pp. 8949-8960, Sept. 2022.

[15] W. Saito, Z. Lou, and S. -i. Nishizawa, "Cutoff Current Capability of SiC-MOSFETs with Parallel Connected Varistor under UIS Condition," *2022 IEEE Workshop on Wide Bandgap Power Devices and Applications in Europe (WiPDA Europe)*, Coventry, United Kingdom, 2022, pp. 1-4.

[16] L. Ravi, D. Zhang, D. Qin, Z. Zhang, Y. Xu, and D. Dong, "Electronic MOV-Based Voltage Clamping Circuit for DC Solid-State Circuit Breaker Applications," in *IEEE Transactions on Power Electronics*, vol. 37, no. 7, pp. 7561-7565, July 2022.

[17] T. Takamori, K. Wada, W. Saito and S. -i. Nishizawa, "Paralleled SiC MOSFETs DC Circuit Breaker with SiC MPS Diode as Avalanche Voltage Clamping," *2022 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Houston, TX, USA, 2022, pp. 225-229.