Paralleling 650 V/150 A GaN HEMTs for Cryogenically Cooled Solid-State Circuit Breaker Applications

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***Abstract*—The significant on-resistance reduction, the faster switching speed, and the capability of being operated at a higher current at cryogenic temperature make Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs) attractive to cryogenically cooled power electronics applications. Moreover, the positive temperature coefficient of on-resistance makes GaN HEMTs suitable for the parallel operation. In this article, the design of a solid-state circuit breaker (SSCB) with two 650V/150A GaN HEMTs in parallel is presented. The designed SSCB circuit is tested at cryogenic temperature (<-153°C). -The results demonstrate the capability of the SSCB module with paralleled GaN-HEMTs to interrupt high current (1000A) at cryogenic temperature.**

Keywords— GaN HEMTs, paralleled GaN HEMTs, solid-state circuit breaker, cryogenic.

I. Introduction

Wide bandgap (WBG) devices such as Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs) are attractive for many power electronics applications due to the characteristics of fast switching, low on-resistance and high breakdown voltage, which directly contribute to the increment of the power density of power electronics converters. Moreover, the on-resistance of GaN-HEMTs is much smaller when temperature drops, which is welcome for the cryogenically cooled applications such as electric aircraft propulsion systems or superconducting machine systems. According to [1] and [2], the on-resistance of GaN-HEMTs exhibits five-times reduction at cryogenic temperatures, which is below -150°C, as compared to that at room temperature.

Another superior characteristic of GaN-HEMTs is the positive temperature coefficient of on-resistances. Owing to the this, current distribution among paralleled dies could be self-balanced, making GaN HEMTs good candidates for parallelization.

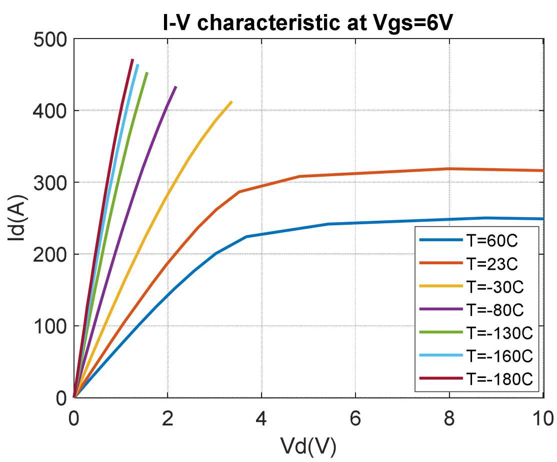
In solid-state circuit breaker (SSCB) applications, main switches are desirable to have low conduction loss and be capable of interrupting high current (e.g., 5~10x) during faults. Thus, paralleling devices is required to achieve high efficiency, and withstand the fault current due to the limited ratings of single device. Paralleling GaN HEMTs in several applications have been published [3]-[7], most of which utilize 650V/60A GaN HEMTs with two or more in parallel to achieve higher current ratings. However, the capability to turn off high current, which is critical in solid-state circuit breaker (SSCB) applications, has not been reported. The capability of GaN HEMTs to interrupt current at cryogenic temperature has been investigated in [2] only with a single 650V/30A GaN- HEMTs device.

In this paper, the 650V/150A GaN-HEMT bare dies are selected for the cryogenically cooled solid-state circuit breaker (SSCB) applications. Two 650/150A GaN HEMTs are paralleled for the SSCB module rated at 100A. TVS configurations with paralleled GaN HEMTs are discussed. Capability of such SSCB module to interrupt high current, such as 10x rated current is evaluated at the cryogenic temperature (<-153°C).

II. SSCB MODULE

A. GaN Devices at Cryogenic Temperature

GaN HEMTs exhibit great characteristics at low temperature such as low on-resistance, and capability of drawing higher current, which are suitable for the cryogenically cooled circuit breaker. Low on-resistance at low temperature results in low conduction loss thereby high efficiency when the SSCBs operate at the normal condition. When the fault occurs in the system, the capability of taking high current enables GaN based SSCBs to withstand the transient current. Moreover, the positive temperature coefficient of on-resistance is also beneficial for paralleling to increase overall current rating of the SSCB module. Fig. 1 shows the I-V characteristic and the on-resistance of the candidate GaN HEMTs, GS-065-150 from GaN Systems at different temperature, measured by Keysight B1505A. Fig 1(a) shows it gets saturated ~300A at the room temperature, while capable of withstanding > 400A at -180°C. Fig. 1(b) presents the positive temperature coefficient of on-resistances of GaN HEMTs, which at -180°C is about one-fifth of that at the room temperature.



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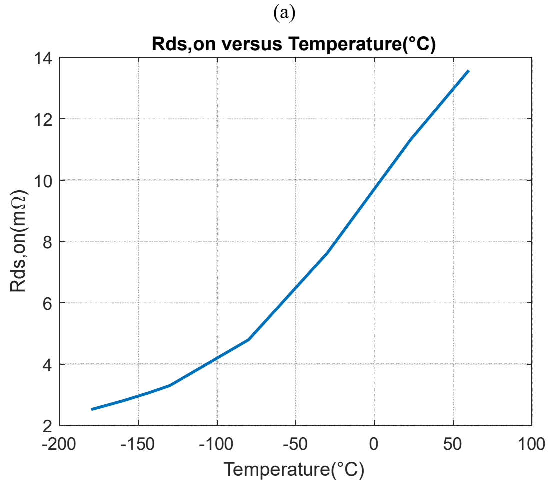


(b)

Fig. 1. Characteristics of GS-065-150 (a) I-V at different temperature (b) Rds(on) versus temperature.

B. Module Design

Fig. 2 shows the typical dc SSCBs circuit, which consists of a semiconductor switch and a voltage clamping circuit. GS-065-150 bare die from GaN Systems is used as the semiconductor switch in SSCB. The high-power Transient Voltage Suppressor (TVS) diode AK3-430C from Littelfuse is selected to absorb the system residual energy and prevent the switch from overvoltage when turning off. Both components are shown in Fig. 3.

Paralleled MOSFETs have a potential instability issue under high current and voltage conditions [8]. High protection

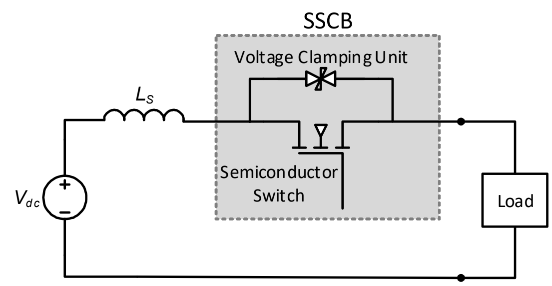


Fig. 2. Typical SSCB in a DC system

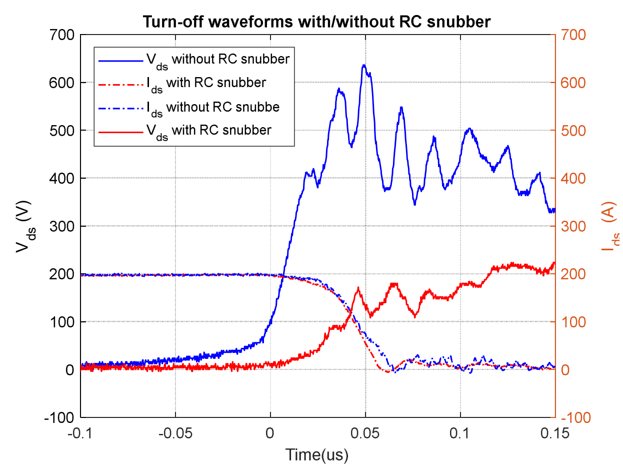
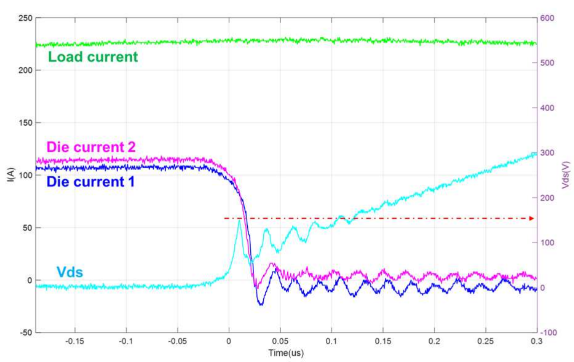


Fig. 3. GaN HEMT turn-off at high current with and without RC snubber

current up to 10x is normal in SSCBs applications [9]-[11]. Thus, the stability issue should be concerned when interrupting such high fault current. The hard switching turn-off at both high current and high voltage lead to a parasitic oscillation and potential failure as shown in Fig. 3. As a result, a RC snubber is added to each die to improve the ringing issue in the turn-off process. The drawback of adding an additional RC snubber is the slower switching speed, which does not fully utilize advantages offered by WBG devices. However, the switching speed is not critical in the SSCB applications. The designed snubber capacitance and resistance are 150 nF and 0.5 Ω, respectively.

In each SSCB module, two GS-065-150 GaN HEMTs are in parallel for the rated 100A SSCB for the sake of high efficiency and capable of interrupting the 10x rated current. The parasitic capacitances of GaN-HEMTSs are much smaller than traditional devices. Thus, a critical design is required to minimize the parasitic inductance in both the gate-drive loop and the power loop [12].

In the SSCB structure, the voltage clamping unit such as a TVS diode is typically paralleled with the switching device or module. During the turn-off, TVS diodes operate to take over the high fault current and clamp the drain-source voltage Vds of the device. The power-loop inductance between the device and the TVS can induce transient voltage spike, which could lead to possible failure when turning off high current shown in Fig. 4. Voltage spike and oscillation can be observed at turning off 200A, as shown in Fig.4(a), and the spike and ringing are further increased in Fig 4(b) that lead to a failure when interrupting 300A. Thus, the configuration of the switching cell and the TVS in the SSCB should be carefully designed. Two switching GaN-HEMT cells and the TVS configurations for the SSCB module are considered and shown in Fig. 5. In Fig 5(a), the TVS is placed on the side of two paralleled GaN devices. The loop inductances between the TVS and each device are not identical. The large loop inductance can induce a significant voltage rise during the turn-off. One solution to mitigate the different loop inductance is shown in Fig 5(b) by moving the TVS to the middle of the paralleled dies. Although the loop is identical from the schematic view, the parasitic inductance might not be the minimum due to the layout design. In this case with two GaN-HEMTs in parallel, the gate-drive circuit sits in the middle to ensure the identical and shorter gate loop, as shown in Fig. 6(a). The power loop thus is affected by the area of the gate driver circuit, which can end up with higher power loop inductance. The other configuration is shown in Fig 5(c). Each device is tied with a TVS to form a cell, which results in a lowest power loop inductance. Such cellular design has the advantages of achieving the lower loop inductance and being independent to the gate drive circuit layout. Moreover, such cellular design can be further applied to more paralleled devices.



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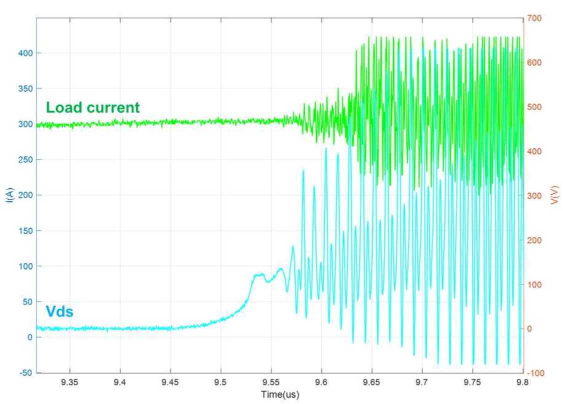
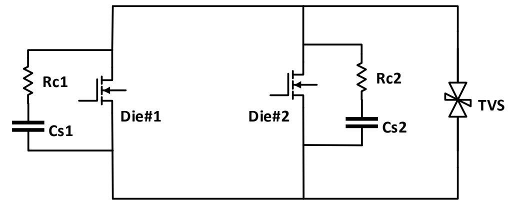


(b)

Fig. 4. Failure waveforms due to large power loop inductance. (a) voltage spike and oscillation due to large loop inductance at 200A turn-off (b) failure with same setting at 300A turn-off



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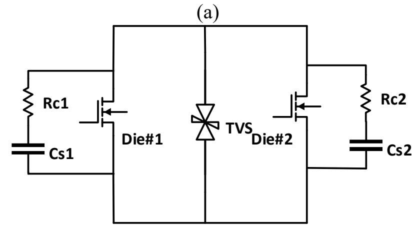

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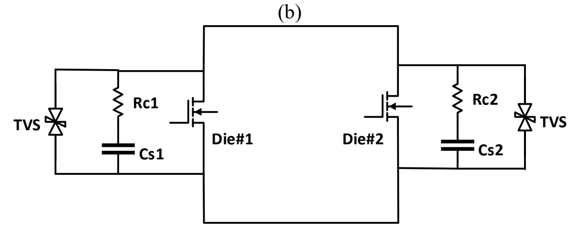


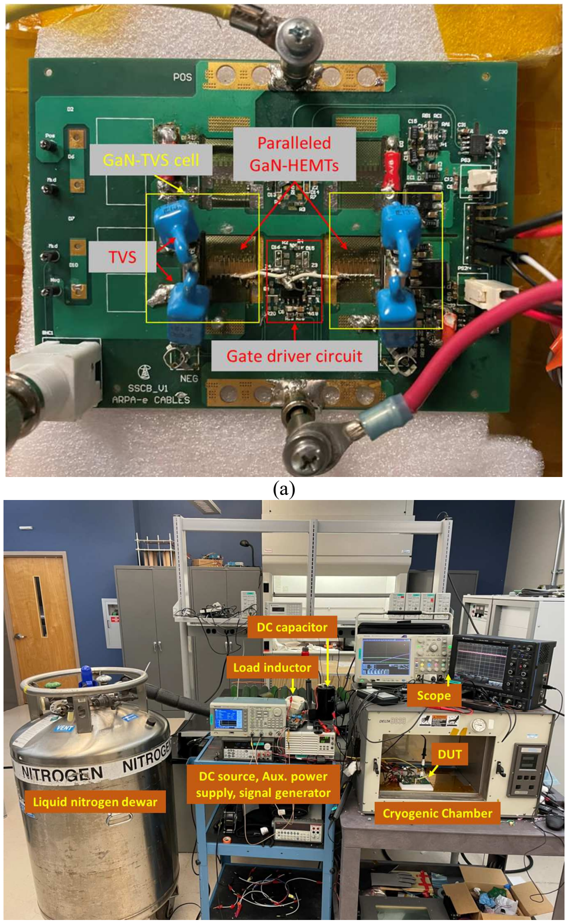
(c)

Fig. 5. Different configuration of TVS with paralleled GaN HEMTs (a) On single side (b) In between (c) Parallel with each die.

III. Test Results

A. Test Setup

The SSCB module and the test platform are shown in Fig. 6. High voltage probe TPP850 is used to measure Vds. Two Rogowski coils are used to measure the current of both dies. Current probe TCP0150 is used to measure the overall load current. Gate voltages are not measured since GaN devices are sensitive to parasitics. Adding the measurement probe could interfere the gate loop with oscillation when shutting down the high current. The SSCB module or the devices under test (DUT) is placed inside the cryo-chamber, which is connected to the liquid nitrogen dewar. Once the testing temperature is set, the liquid nitrogen will be poured into the chamber to control the temperature to emulate the low temperature by the cryogenically cooling system.



(a)

(b)

Fig. 6. Test setup. (a) SSCB module with TVS paralleled to each GaN die (b) Overall test setup

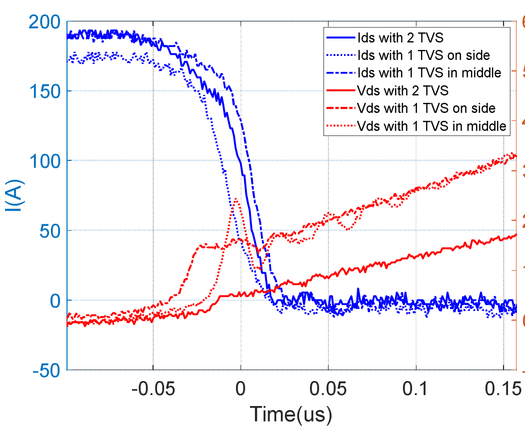


Fig. 7. Turn-off waveforms with different TVS configuration.

B. SSCB Module Test

Three TVS configurations are evaluated by turning off 200A at room temperature. Fig. 7 shows the waveforms of different TVS configurations. With one TVS being placed on the side, the power loop inductance between each die and TVS are non-identical, which induces a 150V voltage spike on Vds during the current commutation, shown as the dashed line in Fig. 7. Moving the TVS in between of two paralleled GaN HEMTs could ensure the identical loop. However, the loop inductance is not minimized because of the existing gate-drive circuit on the layout, as shown in the middle of Fig. 6(a). A higher voltage spike around 240V can be observed from Fig. 7 in the dotted line. By applying the TVS closely to each device, the power loop inductance can be identical and minimized. The ringing is effectively mitigated during the current commutation.

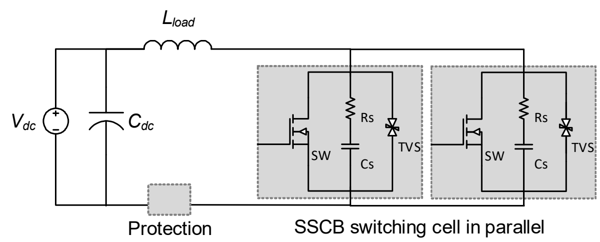
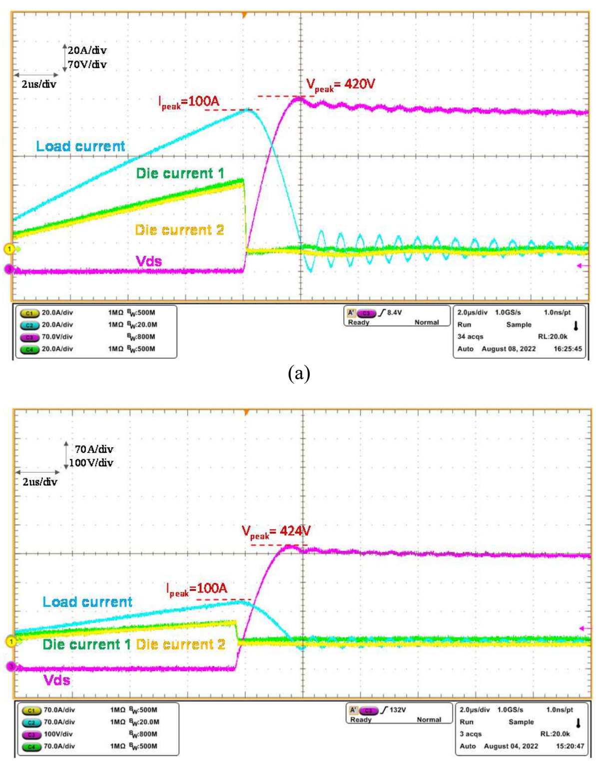


Fig. 8. Circuit diagram for testing paralleled GaN HEMTs.



(a)

(b)

Fig. 9. Test result of the SSCB module turning off at rated current (a) at room temperature (b) at -180°C

The voltage spike when turn-off the device is only around 50V. The estimated loop inductance for each case is 38nH, 65nH and 12nH, respectively.

C. High Current Turn-off of SSCB module with GaN in Parallel

The circuit diagram for testing GaN HEMTs in parallel is shown in Fig. 8. A switching cell consists of one GaN device in parallel with a RC snubber and a TVS. Two GaN-TVS cells are paralleled as shown in Fig. 6(a). The pulse is given to the SSCB with the duty cycle calculated based on the target current level and load inductance. Devices turn off once the current reach the desired current and the snubber takes over to limit the dv/dt until TVS is activated and clamps Vds. Base on the I-V characteristic measured in Fig. 1, the SSCB module is capable of turning off over 300A per device at room temperature, and able to shut down 1000A in total at -180°C, which is 10x of the SSCB rated current.

Fig. 9 shows the result of the SSCB turning off rated 100A load current, and Fig. 10 shows the result of the SSCB turning off 400A load current, both at room temperature and at the cryogenic temperature. The current is evenly flowing through two paralleled GaN HEMTs. No significant voltage spike is observed when TVS is closely attached to the GaN die. The TVS shows a lower breakdown voltage at lower temperature, where the voltage spike due to loop inductance and the foldback characteristic can be observed in Fig 10(b). Fig. 11 shows the SSCB capability to interrupt 1000A, which is about 10x of rated SSCB current, at -180°C. For each device, more than 3x overcurrent is achieved of the selected GaN HEMT die. The clamping voltage at 1000A is around 540V. The current sharing between two paralleled GaN dies is slightly different due to the variation of their characteristics. At the fault condition with high current shown in Fig 11, the current difference is only about 70A before turning off, which is still acceptable in the real practice.

IV. Conclusion

This paper paralleled two 650V/150A GaN bare dies for the cryogenically cooled SSCBs. Different TVS configurations with paralleled GaN HEMTs are investigated. To mitigate the ringing during the current commutation, two TVSs are placed in parallel to each GaN HEMTs to minimize the loop inductance. Test results show the SSCB module with GaN HEMTs in parallel is capable of interrupting 10x rated current of the SSCBs.

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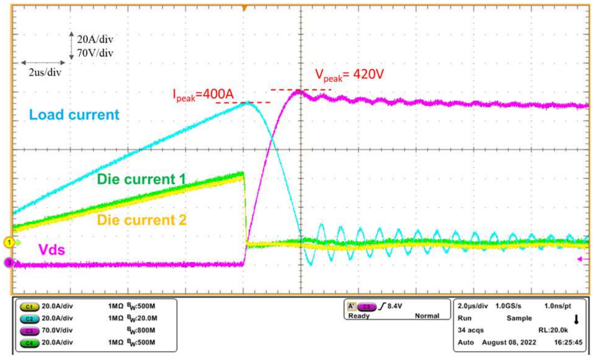

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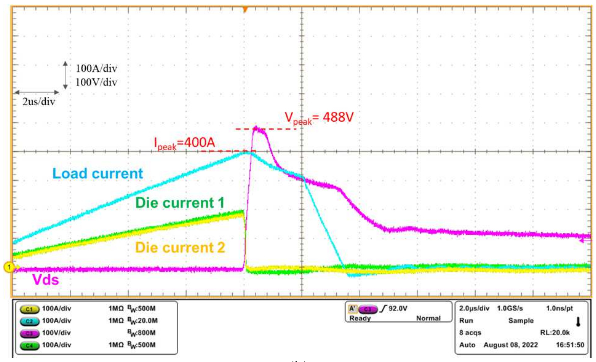

(b)

Fig. 10. Test result of SSCB module turning off 400A (a) at room temperature (b) at -180°C

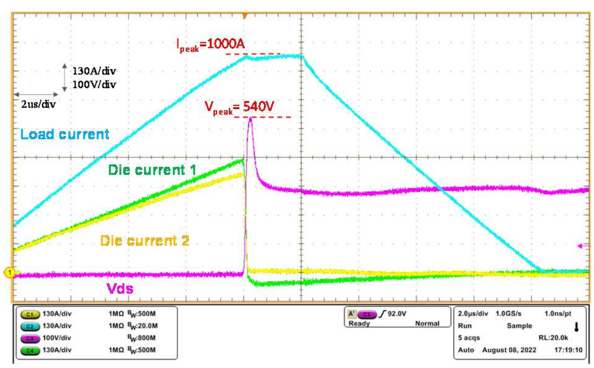

Fig. 11. Test result of SSCB module turning off 1kA at cryogenic temperature (-180°C).

References

[1] R. Ren et al., "Characterization and Failure Analysis of 650-V Enhancement-Mode GaN HEMT for Cryogenically Cooled Power Electronics," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 8, no. 1, pp. 66-76, March 2020, doi: 10.1109/JESTPE.2019.2949953.

[2] R. Chen and F. F. Wang, "SiC and GaN Devices With Cryogenic Cooling," in IEEE Open Journal of Power Electronics, vol. 2, pp. 315-326, 2021, doi: 10.1109/OJPEL.2021.3075061.

[3] N. Haryani, J. Wang and R. Burgos, "Paralleling 650 V/ 60 A GaN HEMTs for high power high efficiency applications," 2017 IEEE Energy Conversion Congress and Exposition (ECCE), 2017, pp. 3663-3668, doi: 10.1109/ECCE.2017.8096649.

[4] J. L. Lu and D. Chen, "Paralleling GaN E-HEMTs in 10kW–100kW systems," 2017 IEEE Applied Power Electronics Conference and Exposition (APEC), 2017, pp. 3049-3056, doi: 10.1109/APEC.2017.7931131.

[5] P. P. Das, S. Satpathy, S. S. Shah, S. Bhattacharya and V. Veliadis, "Paralleling of Four 650V/60A GaN HEMTs for High Power Traction Drive Applications," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), 2021, pp. 5269-5276, doi: 10.1109/ECCE47101.2021.9595766.

[6] H. H. Sathler et al., "Design of three-level flying-capacitor commutation cells with four paralleled 650 V/60 A GaN HEMTs," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021, pp. 2277-2284, doi: 10.1109/APEC42165.2021.9487160.

[7] T. Sawada, H. Tadano, K. Shiozaki and T. Isobe, "Continuous Operation of High-Power Half-Bridge with 12 Paralleled GaN Power Devices," 2022 International Power Electronics Conference (IPEC-Himeji 2022-ECCE Asia), 2022, pp. 157-160, doi: 10.23919/IPEC-Himeji2022-ECCE53331.2022.9806956.

[8] Z. Dong, R. Ren, W. Zhang, F. F. Wang and L. M. Tolbert, "Instability Issue of Paralleled Dies in an SiC Power Module in Solid-State Circuit Breaker Applications," in IEEE Transactions on Power Electronics, vol. 36, no. 10, pp. 11763-11773, Oct. 2021, doi: 10.1109/TPEL.2021.3068608.

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

[10] Electrical Accessories—Circuit-Breakers for Overcurrent Protection for Household and Similar Installations—Part 1: Circuit-Breakers for a.c. Operation, 2015.

[11] Electrical Accessories—Circuit-Breakers for Overcurrent Protection for Household and Similar Installations—Part 2: Circuit-Breakers for AC and DC Operation, 2016.

[12] J. Lu, H. Bai, A. Brown, M. McAmmond, D. Chen and J. Styles, "Design consideration of gate driver circuits and PCB parasitic parameters of paralleled E-mode GaN HEMTs in zero-voltage-switching applications," 2016 IEEE Applied Power Electronics Conference and Exposition (APEC), 2016, pp. 529-535, doi: 10.1109/APEC.2016.7467923.