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Lifetime (B_x) improvement of PV inverter using Si-SiC H-IGBT/Diode: a reliability approach

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ABSTRACT

Technological advancements have made it possible to harness the power of renewable energy sources. The efficiency of power electronic devices has increased to almost 98%. In order to reduce the risks of failure and maintain the operation of photovoltaic (PV)-based energy converters, reliable devices are needed. Due to the increasing number of wide-bandgap silicon in electronic converters, the need for more efficient and reliable devices has become more prevalent. However, the cost of these devices is a major issue. Hence, in this work extensive analysis of hybrid silicon (Si)-IGBT and silicon carbide (SiC) antiparallel Diode (H-IGBT/Diode) based PV inverter is proposed to improve the lifetime (Bx). A reliability oriented lifetime assessment is performed on a test case of single stage three kilowatt photovoltaic inverter with 600 V/30 A hybrid switch. Long term mission profile for one year is considered for evaluation at B. V. Raju Institute of Technology (BVRIT), Telangana, India. Finally, B10 lifetime is calculated, comparison analysis is presented between conventional Si-IGBT and proposed Si-SiC H-IGBT/Diode. The results of the study revealed that the H-IGBT exhibited a significant increase in PV inverter reliability.

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1. INTRODUCTION

Due to the increasing number of RES, the need for power electronic devices has also increased. In most systems, the cost of power electronic converters is around 59%. Thermal stress is a common issue that affects power semiconductors. It can cause various issues, such as solder-die fatigue and lift-off [1]. Due to the high cost of maintaining power electronic devices, it is important that they are modified to reduce their risk of failure. To provide high reliability, power electronic devices are required for photovoltaic (PV) energy conversion systems. Due to the limitations of current-generation power electronic devices, such as those based on Si, conventional switches are not able to meet the needs of the market [2], [3]. A type of power electronic switch that is based on silicon carbide (SiC) technology offers a wide bandgap, which makes it more effective than its conventional counterparts. The other advantages of this type of device include its high switching speed and low switching losses. The rising cost of SiC components is one of the biggest concerns for the PV inverter market. Since it is not feasible to replace every device in the system with this type of technology, hybrid solutions have been proposed [4].

The mathematical model for the turn-off process of a hybrid switch is established by performing a double pulse test. The factors that influence the turn-off velocity and working conditions of the switch are analyzed in [5]. The characteristics of SiC and IGBTs, which are commonly used in SSC, are studied in [6].

In addition, the junction temperature and load current laws are analyzed. Yin *et al.* [7] developed a hybrid FBSM that features a SiC IGBT and a SiC MOSFET. In addition, a control scheme is proposed that will optimize the current path of the FBSM. It will also concentrate the high-frequency switching on the SiC module and improve its compatibility with the MMC modulation scheme. Woldegiorgis *et al.* [8] presented an extensive evaluation and comparison of different gate control techniques, as well as various packaging approaches. It also offers a general guideline for choosing the right approach for specific applications. The study highlights the advantages of utilizing Si/SiC materials and provides a comprehensive understanding of their switch design characteristics.

The dual-inverter configuration, which combines the SiC-MOSFET and Si-IGBT technologies, can be used in cars with premium class driving characteristics and lower power consumption are proposed in [9]. Efficient results and logical arguments support the concept are presented in this research. Bei and Le [10] proposed an optimized switching mode for the hybrid parallel devices based on the characteristics of the SiC IGBT/MOSFET devices. Walter and Bakran [11] aims to improve the overall power loss of a traction inverter that is operating at a DC-Link voltage of 400 V. It utilizes a 650V Freewheeling Diode and a 650 V Si-MOSFET dual in parallel. In addition, it presents a method to decouple the IGBT/SIGBT and SiC-MOSFET halves by using a small inductance. The relationship between the gate turnoff time and the power loss of the Si/SiC hybrid switch has been studied in [12]. It has been revealed that the optimal delay time is between 1 and 2 seconds, which can be used for the switch's minimum turn-off loss. Increasing the working current of the hybrid switch will also decrease the delay time. Cheng *et al.* [13] developed a 30 kW 12 V iHPM incorporating 30 kHz SiC/Si integrated technology. It will be used in industrial drive applications such as motors for variable frequency drives. Diao *et al.* [14] proposed a 5-level hybrid ANPC converter with an inner-interleaved design. It features improved output quality and an easier filtering design. The converter is composed of various low-frequency switching cells and high-frequency MOSFETs. The cost-effective and high-efficiency of this converter are mainly attributed to its low-noise characteristics. Diao *et al.* [15] presented a megawatt-sized MV hybrid electric power conversion prototype. Related works are presented in [16]–[23]. It aims to evaluate the feasibility of this technology in the next-generation aircraft system. In addition to being able to provide electric propulsion, this prototype can also be used onboard a 3-kilowatt DC bus.

In this paper hybrid silicon (Si)-IGBT and SiC antiparallel diode (H-IGBT/Diode) based PV Inverter is proposed to improve the lifetime (B_x). A reliability oriented lifetime assessment is performed on a test case of single stage three kilowatt photovoltaic inverter with 600 V/30 A hybrid switch. Long term mission profile for one year is considered for evaluation at BVRIT, Telangana, India. Junction temperature (T_J) is calculated for corresponding mission profile. T_J variations are analyzed using the rainflow counting (C_R) algorithm. Monte Carlo simulation (S_{MC}) approach is utilized and generated 20,000 samples with five percentage variation. Finally, B_{10} lifetime is calculated at component level (L_C) and system level (L_S). Comparison analysis is presented between conventional Si-IGBT and proposed Si-SiC H-IGBT/Diode. The results of the study revealed that the H-IGBT exhibited a significant increase in PV inverter reliability.

2. PROPOSED Si-SiC H-IGBT/DIODE SWITCH FOR PV INVERTER

The use of silicon carbide in power electronic devices has revolutionized the way we think about power electronics. Its exceptional thermal conductivity and wide bandgap enable the development of innovative switches that are capable of operating at high temperatures and voltages. Switching devices for high-voltage applications, such as power converters and electric cars, are commonly made using silicon carbide. Its various advantages, such as its compact size and better efficiency, make it a suitable choice for numerous industries. Due to the significant cost and complexity of silicon carbide switches, several companies, such as Infineon, STMicroelectronics, and Cree, have been leading the way in producing these components. These companies contributions have helped push the envelope of power electronics [24]–[26]. The Comparison of Si and SiC are presented in Table 1. Still SiC based switches are not economical in this paper Si-SiC H-IGBT/Diode based photovoltaic inverter is proposed as shown in Figure 1. The proposed system is implemented in PLECS environment. The Si-IGBT thermal model is based on the Infineon manufacturer. On the other hand, the SiC-Diode model is from the wolfspeed manufacturer.

Table 1. Comparison

Material	Breakdown voltage (10^6 V/cm)	Thermal conductivity (λ)	Bang gap (eV)
Silicon (Si)	0.3	1.5	1.1
Silicon Carbide (SiC)	2.4	4.5	3.3

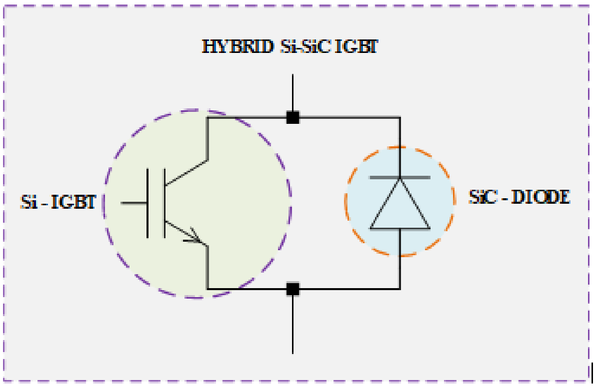


Figure 1. Proposed H-IGBT/Diode

3. RELIABILITY ORIENTED LIFETIME (B_x) ASSESSMENT METHOD

The reliability-oriented lifetime (B_x) assessment method follows several steps. To consider environmental conditions, long term mission profile i.e., Solar Irradiance (I_{RR}) and Ambient Temperature (T_A) for one year is considered for evaluation at B V Raju Institute of Technology (BVRIT), Telangana, India in step 1. T_J is calculated using Foster ETM in the step 2. T_J variations are analyzed using the rainflow counting (C_R) algorithm in step 3. Bayerer's lifetime (L_F) equation is used to calculate the lifetime as shown in (1):

$$L_F = \frac{1}{\sum \frac{N_i}{K(\Delta T_j)^{\beta_1} . e^{\frac{\beta_2}{(T_j + 273K)}} . t_{on}^{\beta_3} . I^{\beta_4} . V^{\beta_5} . D^{\beta_6}}} \quad (1)$$

S_{MC} approach is utilized and generated 20,000 samples with five percentage variation in step 4. The distribution of the generated 20,000 samples were carried out through the Weibull process and the R(t) is calculated as follows:

$$R(t) = e^{-\left(\frac{t}{\propto}\right)^{\gamma}} \quad (2)$$

where $\propto$ = scale parameter.
γ = shape parameter.

$$R_{total}(t) = \prod_{i=1}^{n} R_i(t) \quad (3)$$

Where $R_i(t)$ individual component reliability.
Finally, reliability-oriented lifetime (B_x) assessment is evaluated in step 5. The detailed flowchart is presented in Figure 2.

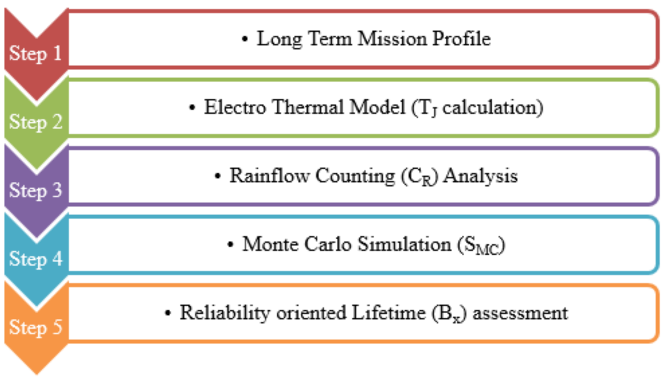


Figure 2. Flowchart

4. TEST CASE

In this work extensive analysis of hybrid silicon (Si)-IGBT and SiC antiparallel Diode (H-IGBT/Diode) based PV Inverter is proposed to improve the lifetime (B_x). A reliability oriented lifetime assessment is performed on single stage three kilowatt photovoltaic inverter with 600 V/30 A hybrid switch as shown in Figure 3. The specifications of the system are tabulated in Table 2.

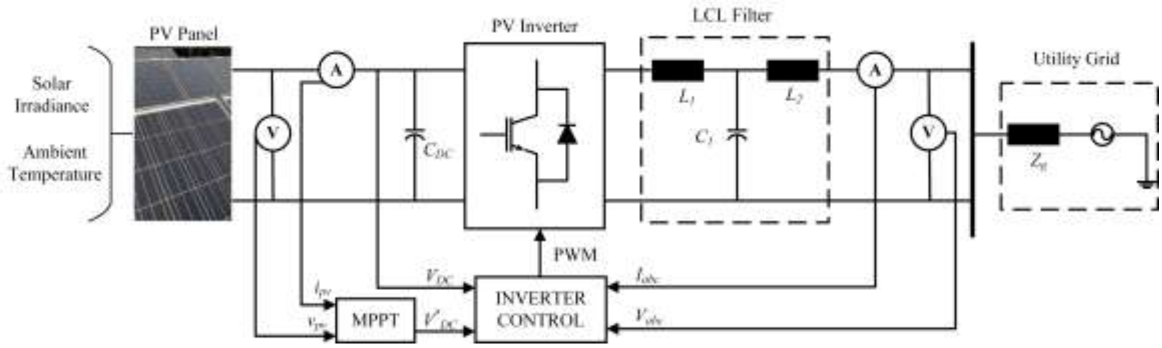


Figure 3. Proposed test case system

Table 2. Parameters

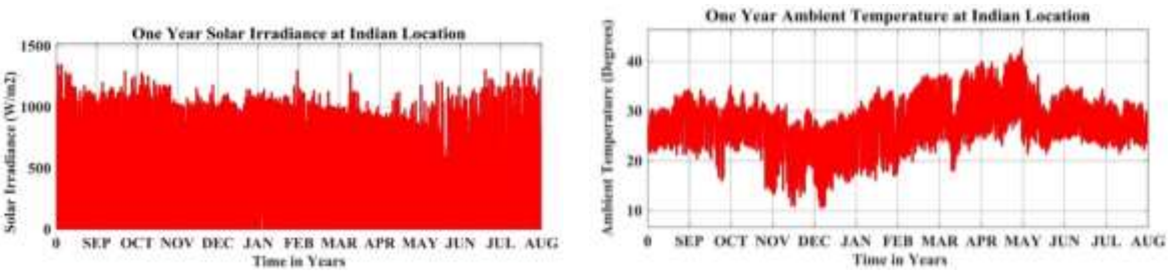
Name	Specification
Model and Make of PV Panel	BP solar (365)
Rating of Inverter	Three kilowatt
RMS Voltage at Grid	230 V
Frequency at Grid	50 Hz

5. RESULTS AND DISCUSSION

In this work reliability oriented lifetime (B_x) assessment. Is evaluated for the proposed Si-SiC H-IGBT/Diode and compared with conventional Si-IGBT. The assessment is carried as per the Figure 2.

5.1. Long term mission profile at BVRIT

To consider environmental variations, long term mission profile i.e., solar irradiance (I_{RR}) and ambient temperature (T_A) for one year is considered for evaluation at B V Raju Institute of Technology (BVRIT), Telangana, India from September 2020 to August 2021. The yearly mission profile is presented in Figure 4. Where solar irradiance (I_{RR}) is presented in Figure 4(a) and ambient temperature (T_A) is presented in Figure 4(b).



(a) (b)

Figure 4. Long term mission profile (a) solar irradiance and (b) ambient temperature

5.2. Electro thermal model

Long term yearly mission profile i.e., I_{RR} and T_A are translated to T_J using the foster electro thermal model. The translated T_A for conventional Si-IGBT and proposed Si-SiC H-IGBT/Diode corresponding to the long term mission is presented in Figure 5. The average T_J for the convention Si-IGBT is 55.66 °C, for proposed H-IGBT/Diode is 53.9 °C. The average T_J is decreased using the proposed H-IGBT/Diode as shown in Figure 6.

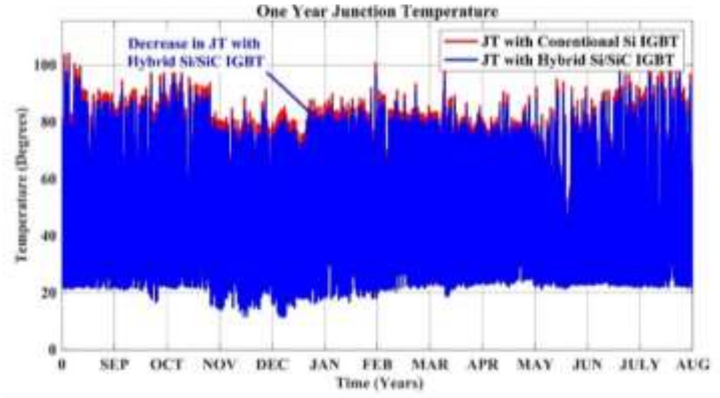


Figure 5. Translated T_J for long term mission profile

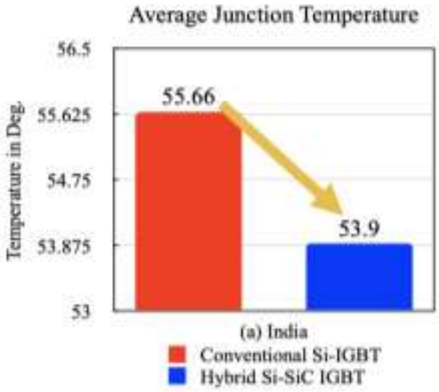


Figure 6. Average T_J

5.3. Rainflow counting (C_R) analysis

To analyze the variations of the translated T_J is analyzed using rainflow counting (C_R). C_R parameters No.of Cycles N_i, mean junction temperature T_{jm}, cycle amplitude ΔT are obtained for both conventional Si-IGBT as shown in Figure 7. Proposed H-IGBT/Diode as shown in Figure 8 respectively.

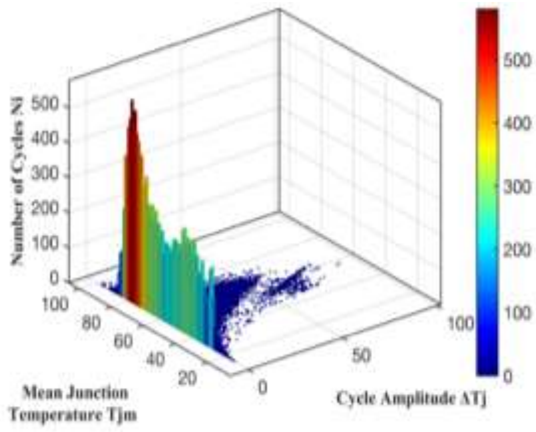


Figure 7. C_R analysis for conventional Si-IGBT

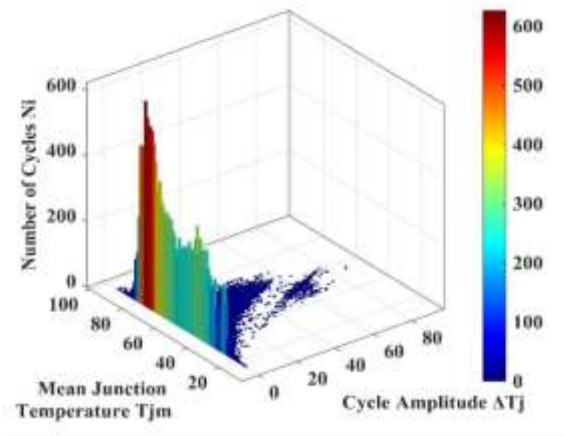


Figure 8. C_R analysis for proposed H-IGBT/Diode

5.4. Monte Carlo simulation (S_{MC})

SMC approach is utilized and generated 20,000 samples with five percentage variation and L_F is calculated at all the samples using (1) and fitted in the Weibull distributions for both conventional Si-IGBT as shown in Figures 9. Proposed H-IGBT/Diode as shown in Figure 10 respectively.

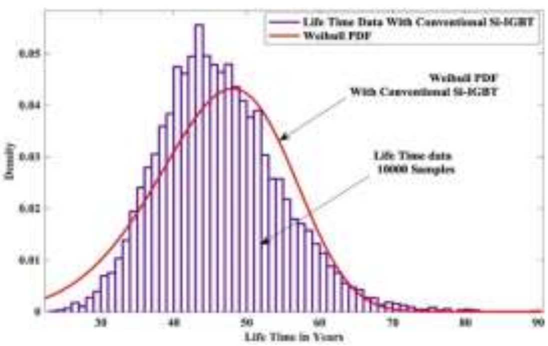


Figure 9. S_{MC} for conventional Si-IGBT

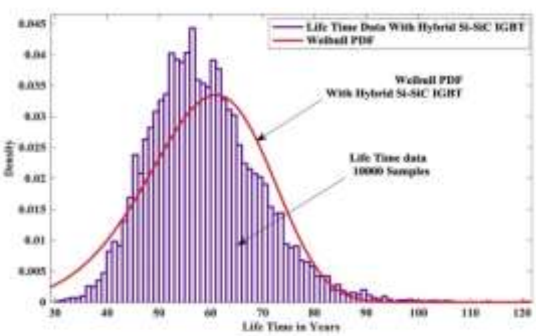


Figure 10. S_{MC} for proposed H-IGBT/Diode

5.5. Reliability oriented lifetime (B_x) assessment

Reliability oriented lifetime (B_{10}) assessment is evaluated for conventional Si-IGBT and proposed H-IGBT/Diode for both L_C and L_S as shown in Figures 11 and 12 respectively. From the above results lifetime (B_x) is improved at both L_C and L_S with the proposed Si-SiC H-IGBT/Diode. At L_C Lifetime (B_x) is improved from 34 years to 42 years. At L_S Lifetime (B_x) is improved from 24 years to 31 years.

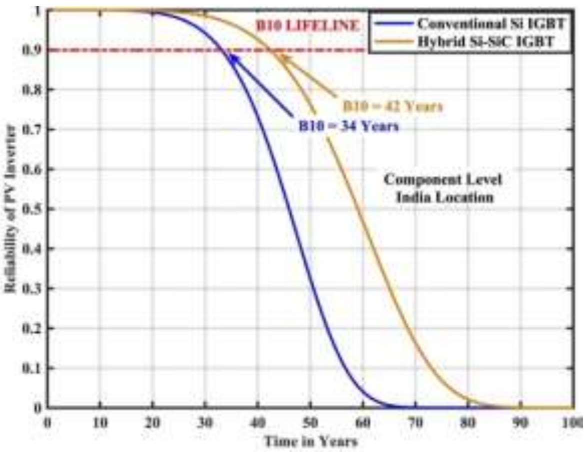


Figure 11. Lifetime (B_x) assessment at L_C

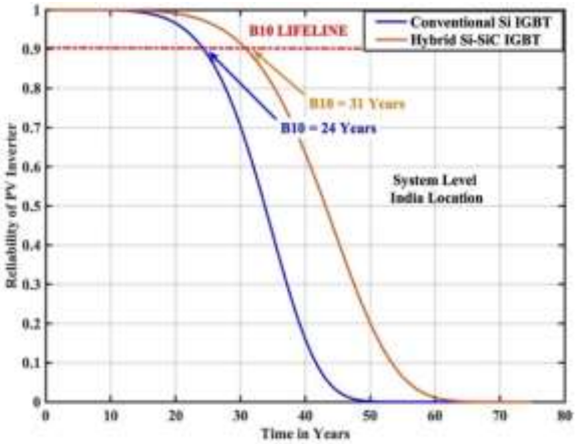


Figure 12. Lifetime (B_x) assessment at L_S

6. CONCLUSION

In this paper hybrid silicon (Si)-IGBT and SiC antiparallel diode (H-IGBT/Diode) based PV inverter is proposed to improve the lifetime (B_x). A reliability oriented lifetime assessment is performed on single stage three kilowatt inverter with 600 V/30 A hybrid switch. Long term mission profile for one year is considered for evaluation at B V Raju Institute of Technology (BVRIT), Telangana, India. Junction temperature (T_J) is calculated for corresponding mission profile. T_J variations are analyzed using the rainflow counting (C_R) algorithm. SMC approach is utilized and generated 20,000 samples with five percentage variation. Finally, B_{10} lifetime is calculated at component level (L_C) and system level (L_S). Comparison analysis is presented between conventional Si-IGBT and proposed Si-SiC H-IGBT/Diode. The results of the study revealed that the lifetime (B_x) is improved at both L_C and L_S with the proposed Si-SiC H-IGBT/Diode. At L_C Lifetime (B_x) is significantly improved from 34 years to 42 years. At L_S Lifetime (B_x) is improved from 24 years to 31 years. In the future the work can be extended by designing the SiC based IGBT.

REFERENCES

[1] S. Nyamathulla, D. Chittathuru, and S. M. Muyeen, "An overview of multilevel inverters lifetime assessment for grid-connected solar photovoltaic applications," *Electronics (Switzerland)*, vol. 12, no. 8. 2023, doi: 10.3390/electronics12081944.

[2] R. K. Gatla *et al.*, "Impact of mission profile on reliability of grid-connected photovoltaic inverter," *Journal Europeen des Systemes Automatises*, vol. 55, no. 1, pp. 119–124, 2022, doi: 10.18280/jesa.550112.

[3] S. S. Kshatri *et al.*, "Reliability analysis of bifacial PV panel-based inverters considering the effect of geographical location," *Energies*, vol. 15, no. 1, 2022, doi: 10.3390/en15010170.

[4] P. Ning, T. Yuan, Y. Kang, C. Han, and L. Li, "Review of Si IGBT and SiC MOSFET based on hybrid switch," *Chinese Journal of Electrical Engineering*, vol. 5, no. 3, pp. 20–29, 2019, doi: 10.23919/CJEE.2019.000017.

[5] H. Qin *et al.*, "Evaluation and suppression method of turn-off current spike for SiC/Si hybrid switch," *IEEE Access*, vol. 11, pp. 26832–26842, 2023, doi: 10.1109/ACCESS.2023.3251397.

[6] Z. Jingwei, W. Qiang, Z. Weifeng, and T. Guojun, "Voltage division investigation of series short-circuit fault on SiC MOSFETs and Si IGBTs," *IET Power Electronics*, vol. 16, no. 2, pp. 333–345, 2023, doi: 10.1049/pel2.12374.

[7] T. Yin, L. Lin, X. Shi, and K. Jing, "A Si/SiC hybrid full-bridge submodule for modular multilevel converter with its control scheme," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 1, pp. 712–721, 2023, doi: 10.1109/JESTPE.2022.3208602.

[8] D. Woldegiorgis, M. M. Hossain, Z. Saadatizadeh, Y. Wei, and H. A. Mantooth, "Hybrid Si/SiC Switches: A review of control objectives, gate driving approaches and packaging solutions," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 2, pp. 1737–1753, 2023, doi: 10.1109/JESTPE.2022.3219377.

[9] H. Matsumori, T. Kosaka, N. Matsui, and S. Saha, "Alternative PWM switching strategy implementation for a dual inverter fed open winding motor drive system for an electric vehicle application," in *IEEE Transactions on Industry Applications*, 2023, vol. 59, no. 5, pp. 5957–5970, doi: 10.1109/TIA.2023.3291340.

[10] B. Bei and C. Le, "Switching mode optimization and characteristic analysis of Si/SiC hybrid parallel devices," *Guti Dianzixue Yanjiu Yu Jinzhan/Research and Progress of Solid State Electronics*, vol. 43, no. 4, pp. 289–295, 2023.

[11] M. Walter and M. M. Bakran, "Optimization of the hybrid-switch inverter by decoupling SiC and Si," in *ICPE 2023-ECCE Asia - 11th International Conference on Power Electronics - ECCE Asia: Green World with Power Electronics*, 2023, pp. 1835–1842, doi: 10.23919/ICPE2023-ECCEAsia54778.2023.10213959.

[12] Y. M. Zhou, S. L. Mu, H. Yang, B. Wang, and Z. Q. Chen, "Optimal gate turn-off delay-time of Si/SiC hybrid switch and its application in inverter," *Tien Tzu Hsueh Pao/Acta Electronica Sinica*, vol. 51, no. 6, pp. 1468–1473, 2023, doi: 10.12263/DZXB.20211094.

[13] H. C. Cheng, Y. C. Liu, H. H. Lin, S. C. Chiou, C. M. Tzeng, and T. C. Chang, "Development and performance evaluation of integrated hybrid power module for three-phase servo motor applications," *Micromachines*, vol. 14, no. 7, 2023, doi: 10.3390/mi14071356.

[14] F. Diao *et al.*, "A medium-voltage multilevel hybrid converter using 3.3kV silicon carbide MOSFETs and silicon IGBT modules," in *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, 2023, vol. 2023-March, pp. 848–853, doi: 10.1109/APEC43580.2023.10131462.

[15] F. Diao *et al.*, "A megawatt-scale Si/SiC hybrid multilevel inverter for electric aircraft propulsion applications," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 4, pp. 4095–4107, 2023, doi: 10.1109/JESTPE.2023.3266197.

[16] J. Rajesh, N. Jayaram, P. S. V. Kishore, and S. Jakkula, "Performance analysis of grid interactive single-phase solar powered fault tolerant cascaded inverter," *International Journal of Emerging Electric Power Systems*, vol. 24, no. 2, pp. 225–240, 2023, doi: 10.1515/ijeeps-2021-0416.

[17] R. Jami, J. Nakka, and S. V. K. Pulavarthi, "Grid integration of three phase solar powered fault-tolerant cascaded H-bridge inverter," *International Journal of Circuit Theory and Applications*, vol. 50, no. 7, pp. 2566–2583, 2022, doi: 10.1002/cta.3272.

[18] Y. Avenas, L. Dupont, N. Baker, H. Zara, and F. Barruel, "Condition monitoring: a decade of proposed techniques," *IEEE Industrial Electronics Magazine*, vol. 9, no. 4, pp. 22–36, 2015, doi: 10.1109/MIE.2015.2481564.

[19] U. M. Choi and J. S. Lee, "Single-phase five-level IT-Type NPC inverter with improved efficiency and reliability in photovoltaic systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 5, pp. 5226–5239, 2022, doi: 10.1109/JESTPE.2021.3103252.

[20] S. Alotaibi and A. Darwish, "Modular multilevel converters for large-scale grid-connected photovoltaic systems: A review," *Energies*, vol. 14, no. 19. 2021, doi: 10.3390/en14196213.

[21] T. Ryu and U. M. Choi, "Discontinuous PWM strategy for reliability and efficiency improvements of single-phase five-level T-Type inverter," *IEEE Transactions on Industrial Electronics*, vol. 71, no. 3, pp. 2567–2577, 2024, doi: 10.1109/TIE.2023.3265046.

[22] U. M. Choi, "Study on effect of installation location on lifetime of PV inverter and DC-to-AC ratio," *IEEE Access*, vol. 8, pp. 86003–86011, 2020, doi: 10.1109/ACCESS.2020.2993283.

[23] J. M. S. Callegari, A. F. Cupertino, V. D. N. Ferreira, and H. A. Pereira, "Minimum DC-link voltage control for efficiency and reliability improvement in PV inverters," *IEEE Transactions on Power Electronics*, vol. 36, no. 5, pp. 5512–5520, 2021, doi: 10.1109/TPEL.2020.3032040.

[24] S. Hazra *et al.*, "High switching performance of 1700-V, 50-A SiC power MOSFET over Si IGBT/BiMOSFET for advanced power conversion applications," *IEEE Transactions on Power Electronics*, vol. 31, no. 7, pp. 4742–4754, 2016, doi: 10.1109/TPEL.2015.2432012.

[25] J. Biela, M. Schweizer, S. Waffler, and J. W. Kolar, "SiC versus Si - evaluation of potentials for performance improvement of inverter and DCDC converter systems by SiC power semiconductors," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 7, pp. 2872–2882, 2011, doi: 10.1109/TIE.2010.2072896.

[26] T. Kimoto and J. A. Cooper, *Fundamentals of silicon carbide technology: growth, characterization, devices and applications*, vol. 9781118313, 2014.

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