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Reliability Assessment of Hybrid Silicon-Silicon Carbide IGBT Implemented on an Inverter for Photo Voltaic Applications

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ABSTRACT

Recent Advancements in the semiconductor technology leads to the use of Silicon Carbide (SiC) materials in the design of power switches due to its wide band gap that performs superior compared to conventional Silicon material. Nevertheless, the cost of manufacturing IGBT with the SiC material is of major concern. Hence, this article proposes a hybrid Si-SiC based IGBT to improve the performance and reliability. The hybrid Si-SiC IGBT consist of Si-IGBT with SiC Feedback Diode. A test case of 600V/30A hybrid Switch (Si-IGBT (IGW30N60H3)/SiC- diode (C3D20060D)) is considered and implemented on a 3 kW PV inverter. Mission Profile oriented reliability analysis is carried out using PLECS thermal model at two different atmospheric conditions and its effectiveness is evaluated in comparison with conventional Si IGBT. Monte Carlo simulation is implemented to calculate the B_{10} lifetime. The population size of 10000 with 5 % variation is considered. The improved B_{10} lifetime and reliability with the proposed hybrid Si-SiC IGBT is obtained at both India and Denmark locations.

KEYWORDS: Hybrid Si-SiC IGBT, Reliability, Lifetime Assessment, PLECS Thermal Model
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1. INTRODUCTION

The increasing popularity of SiC power MOSFETs has resulted in significant improvements in their efficiency and power density. These devices are commonly used in power electronic devices. In [1] author presented A partial-power slave unit with SiC MOSFET which is connected to a line-frequency transformer to compensate the harmonics of the input mu, and it adjusts the output voltage. This new topology is designed to provide reliable operation. The components of this system are also introduced in detail to ensure the continuous operation. In [2] Author proposed Cross hybrid design is a concept that combines the advantages of both a 3.3-kV IGBT and a SiC MOSFET. It can be used to perform calibrations in 2D TCAD software. In [3] proposed hybrid switch that combines the advantages of both the IGBT and the SiC diode. It consists lower switching loss and a higher power density than that of an IGBT. The performance of this system is expected to improve the power density of a traditional converter system. A parallel arrangement of a SiC and IGBT hybrid switch has been presented in [4]. The aim of this concept is to achieve better performance and lower dynamic losses while improving the thermal and electrical properties of the device. The combination of the two components is expected to lead to better electrical and thermal properties

Despite the advantages of SiC power MOSFETs, their cost is still higher than those of the other types of power electronic devices. This is one of the main reasons why the market for this technology is still not growing [5]-[6]. A hybrid device solution that combines a SiC power transistor with a feedback diode was proposed to address the cost challenge. This technology could be an ideal alternative to traditional power electronic devices. The hybrid device solution, offers a low turn-on switching loss and a smaller cost than a full-sized SiC power transistor. In [7], a 6.5-kV Si-IGBT is combined with a 6.5-kV feedback diode. Compared to the conventional devices, this hybrid solution provides better power density, efficiency and the lowest reverse recovery loss, which is considered to be the most significant factor that led to its superior turn-on loss performance. In [8] presented 4.5-kV hybrid IGBT. Compared to the conventional devices, the turn-on loss of the IGBT decreased by about 30%. The results of the study also indicated that the feedback diode performance improved significantly.

The performance of the hybrid module was also significantly improved for commercial applications, such as 600 V and 1200 V. Compared to the conventional devices, it exhibited a 40% reduction in turn-on switching loss [9]-[10]. Several companies have started to introduce hybrid switches. Some of these include Semikron and On Semiconductor. These switches are designed for 600 V and 1200 V applications. The conventional switch has a high tail current. This condition leads to large turn-off switching loss when the device is operating at high voltage. The knee voltage drop caused by the feedback diode also increases the device's conduction loss. The hybrid switch can overcome these problems.

The current research lacks in reliability oriented performance assessment of hybrid switch. Hence in this paper Hybrid Silicon-Silicon Carbide IGBT for Photo Voltaic Applications is proposed and comparative reliability assessment is presented. The hybrid Si-SiC IGBT consist of Si-IGBT with SiC Feedback Diode. A test case of 600V/30A hybrid Switch (Si-IGBT (IGW30N60H3)/SiC- diode (C3D20060D)) is considered and implemented on a 3 kW PV inverter. Mission Profile oriented reliability analysis is carried out using PLECS thermal model at two different atmospheric conditions and its effectiveness is evaluated in comparison with conventional Si IGBT. Monte Carlo simulation is implemented to calculate the B10 lifetime ("Probability to fail 10 % of the population"). The population size of 10000 with 5 % variation is considered. The improved B10 lifetime and reliability with the proposed hybrid Si-SiC IGBT is obtained at both India and Denmark locations.

2. HYBRID Si-SiC IGBT

Silicon carbide, which has a higher breakdown voltage, is a promising material for power switches. Because of its high blocking voltages, these devices can have better resistances than their Si switches. The higher band-gap and thermal conductivity of silicon carbide allow it to perform better at higher temperatures. Its properties have been widely discussed in the field of power electronics for several decades. The properties of Si and SiC materials are compared and tabulated in Table 1. The proposed hybrid Silicon-Silicon Carbide IGBT is presented in Figure 1. The thermal model of Si IGBT is taken from IGW30N60H3 Infineon data sheet and SiC diode is taken from C3D20060D wolfspeed data sheet. The IGBT with Si/SiC Diode Turn On and Turn OFF Characteristics are presented in Figure 2 and 3.

Table 1. Properties of Si-SiC materials

Property	Si Material	SiC Material
Band Gap (eV)	1.1	3.3
Thermal Conductivity (λ)	1.5	4.5
Breakdown Voltage (10^6 V/cm)	0.3	2.4

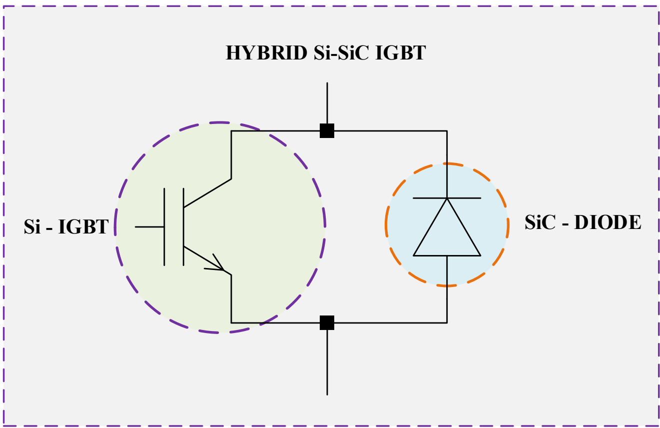


Figure 1. Proposed Hybrid Si-SiC IGBT

Figure 2 depicts that the current taken by SiC diode during turn on is less than the conventional Si diode. Similarly, the figure 3 shows that the reverse saturation current during turn off is less and it quickly comes to the off state compared to the conventional Si diode.

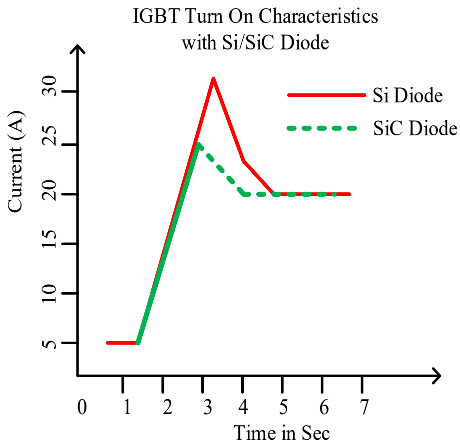


Figure 2. Turn On Characteristics

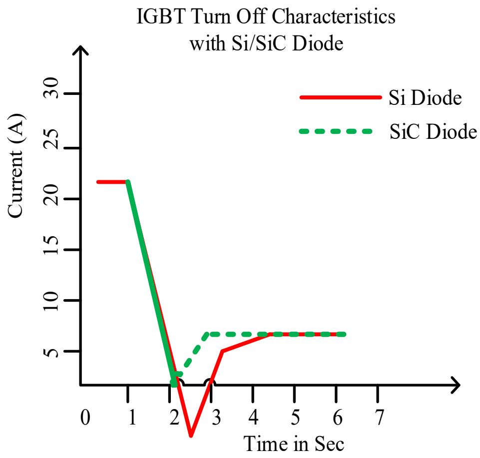


Figure 3. Turn Off Characteristics

3. RELIABILITY ASSESSMENT METHODOLOGY

In this paper mission profile oriented reliability assessment is carried out at two different atmospheric conditions as shown in figure 4. One is hot atmospheric conditions i.e. India and the other is cold atmospheric condition i.e. Denmark. Solar Irradiance and Ambient Temperature with one-minute resolution for one year from Sep'18 to Aug'19 is considered as mission profile. At India mission profile taken from [11], similarly, at Denmark it is taken from [12]. The rainflow analysis, Monto Carlo simulation are implemented for analysis. [13]-[14].

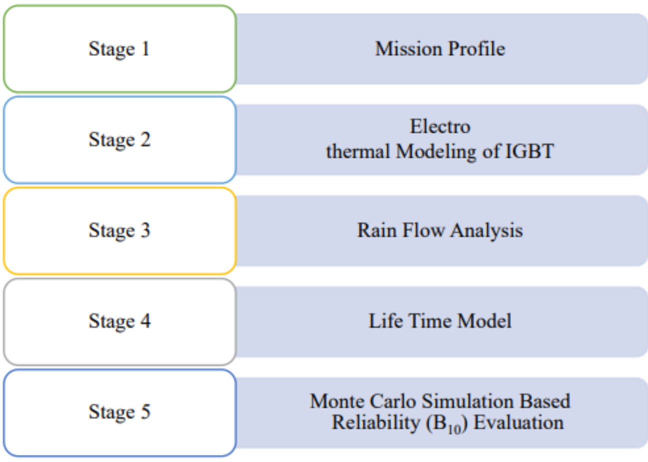


Figure 4. Reliability Assessment Flowchart

4. CASE STUDY

In this paper the proposed Hybrid Si-SiC IGBT is implemented on a 3 kW grid connected PV inverter (Single Phase) as shown in figure 5. The specifications are tabulated in table 2.

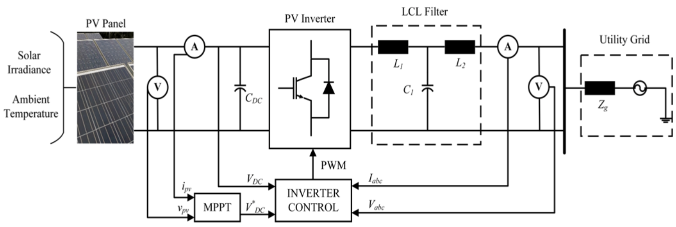


Figure 5. Hybrid Si-SiC switch based PV System

Table 2. Specifications

Name	Specification
PV panel model	BP365 (Model Number)
PV inverter rated power	3-kW
Grid voltage	230 V
Grid frequency	50 Hz
Dc link capacitance	1.5e-3 F

In the case study BP365 PV panels are considered. The PV inverter is designed as single phase H bridge and consists of four switches. Reliability assessment is performed at both component level (Single IGBT) and system level (Four IGBT's).

5. RESULTS AND DISCUSSION

In this paper mission profile oriented reliability assessment is carried out on 3 kW PV inverter considering proposed Hybrid Si-SiC IGBT under the following cases.

1. Reliability Assessment of Hybrid Si-SiC IGBT at Hot (India) Atmospheric Condition
2. Reliability Assessment of Hybrid Si-SiC IGBT at Cold (Denmark) Atmospheric Condition

5.1 Reliability Assessment of Hybrid Si-SiC IGBT at Hot (India) Atmospheric Condition

In this case reliability performance of proposed switch is assessed in comparison with conventional switch at Hot (India) atmospheric condition.

5.1.1 Mission Profile

Mission Profile (Solar Irradiance & Ambient Temperature) is logged for one year with one-minute resolution at Indian atmospheric condition from Sept'18 to Aug'19 as shown in figure 6.

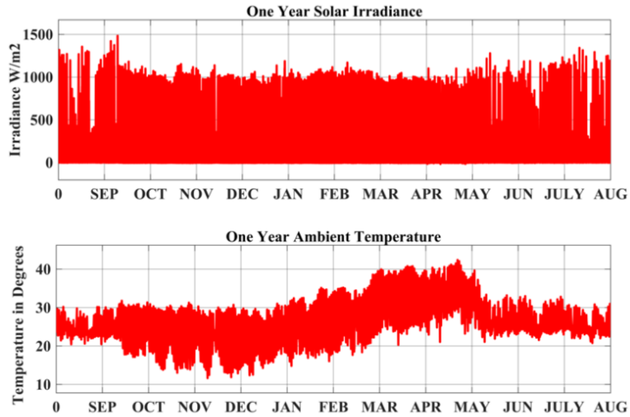


Figure 6. Mission Profile at Hot (India) atmospheric condition

In India, the maximum ambient temperature is recorded in March to June and the lowest in November to February. The maximum solar radiation is recorded in March, April, and May and in the remaining months moderate values are recorded.

5.1.2 ETM of IGBT

In this paper foster Electro Thermal model is considered to extract the junction temperature from the logged mission profile. The junction temperature is extracted for both conventional and proposed switch as shown in figure 7.

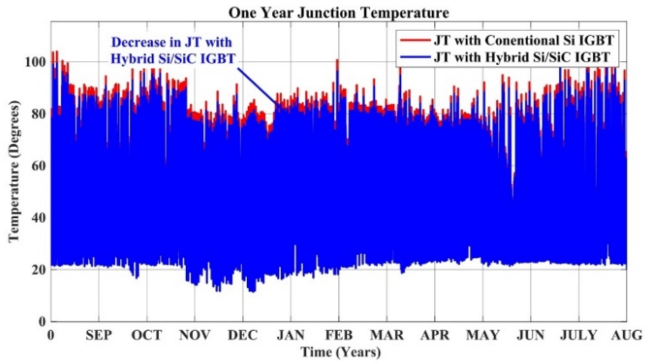


Figure 7. Junction temperature

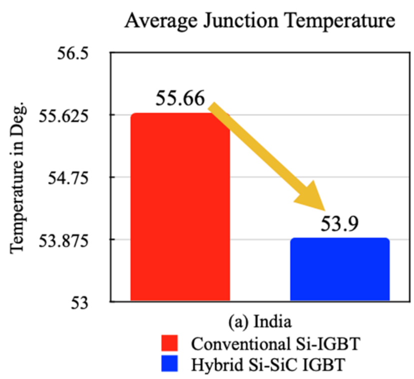


Figure 8. Average Junction Temperature

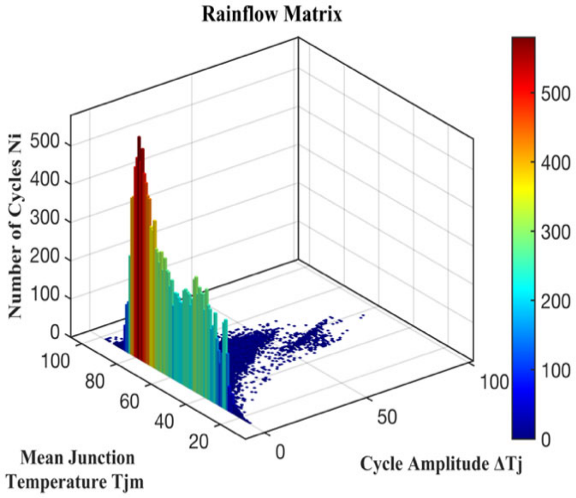
Junction temperature exhibits the decreased trend with proposed switch. The average junction temperature decreased from 55.66 ^{0}C to 53.9 ^{0}C with proposed switch as shown in figure 8.

5.1.3 RF analysis of Junction Temperature

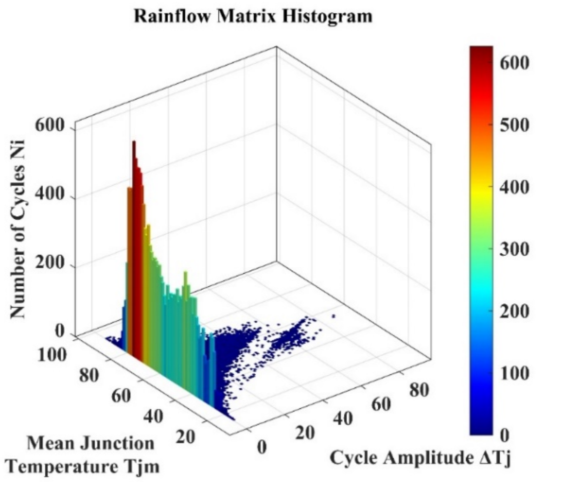
The extracted junction temperature follows irregular profile and it is difficult to analyses hence rainflow counting algorithm is used to analyse it. The following parameters are extracted for both conventional and proposed switch.

- No.of Cycles N_i,
- Mean Junction Temperature T_{jm},
- Cycle Amplitude ΔT.

The corresponding rainflow histogram is presented in figure 9.



(a) Rainflow Matrix with Si-IGBT



(b) Rainflow Matrix with Si- SiC IGBT

Figure 9. RF analysis

5.1.4 MCS analysis and B_{10} lifetime calculation

Based on the parameters of RF analysis, Monte Carlo simulation is implemented to calculate the B_{10} lifetime. The population size of 10000 with 5% variation is considered. Component level and system level B_{10} lifetime curve are plotted for both conventional and proposed switch as shown in figure 10.

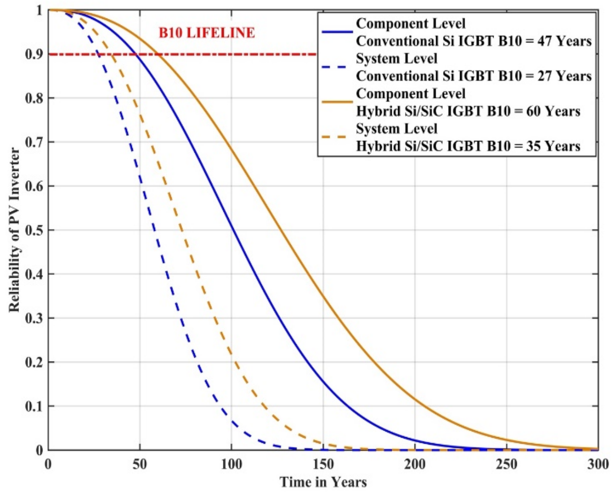


Figure 10. B_{10} lifetime curves

The B_{10} lifetime is improved with proposed switch at both component level and system level. At component level B_{10} lifetime is improved from 47 years to 60 years. Similarly, at system level B_{10} lifetime is improved from 27 years to 35 years.

5.2 Reliability Assessment of Hybrid Si-SiC IGBT at Cold (Denmark) Atmospheric Condition

In this case reliability performance of proposed switch is assessed in comparison with conventional switch at Cold (Denmark) atmospheric condition.

5.2.1 Mission Profile

Mission Profile (Solar Irradiance & Ambient Temperature) is logged for one year with one-minute resolution at Denmark atmospheric condition from Sept'18 to Aug'19 as shown in figure 11.

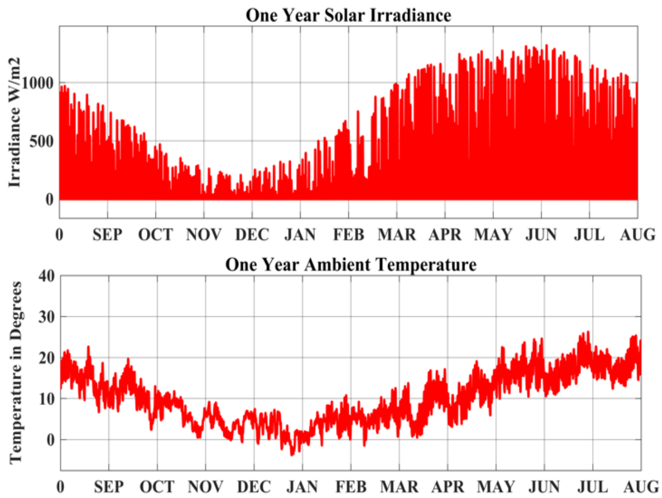


Figure 11. Mission Profile at Cold (Denmark) atmospheric condition

In Denmark, the maximum ambient temperature is recorded in May to August and the lowest in December to March. The minimum solar radiation is recorded in September, October, November, December, January, February, March and in the remaining months maximum values are recorded.

5.2.2 ETM of IGBT

In this paper foster Electro Thermal model is considered to extract the junction temperature from the logged mission profile. The junction temperature is extracted for both conventional and proposed switch as shown in figure 12.

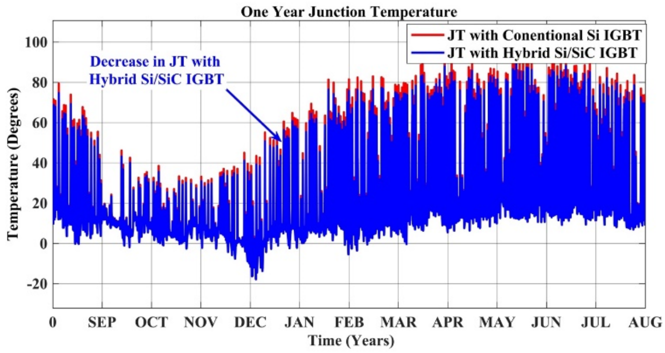


Figure 12. Junction temperature

Junction temperature exhibits the decreased trend with proposed switch. The average junction temperature decreased from 16.38 ^{0}C to 15.91 ^{0}C with proposed switch as shown in figure 13.

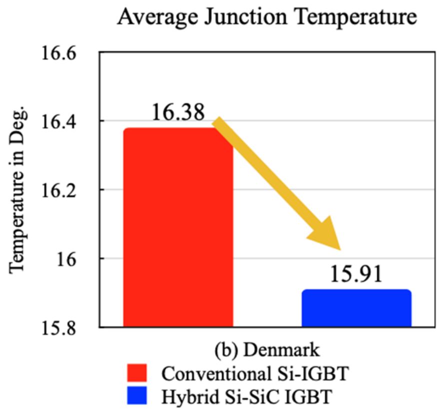
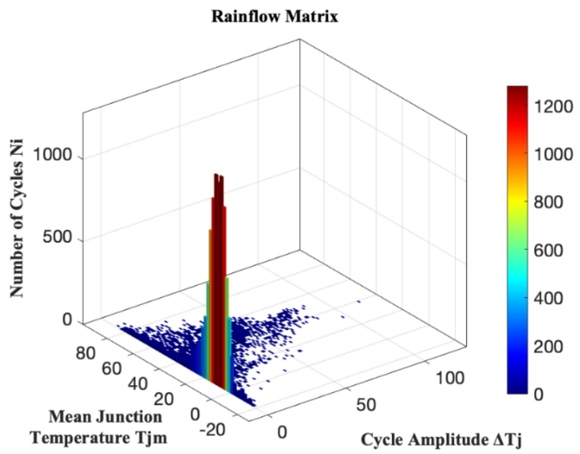


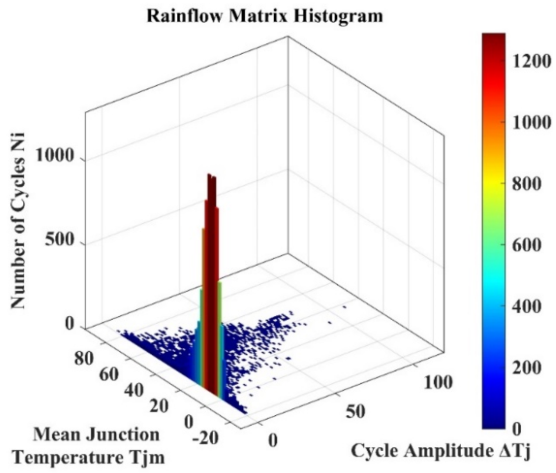
Figure 13. Average Junction Temperature

5.2.3 RF analysis of Junction Temperature

The extracted junction temperature follows irregular profile and it is difficult to analyses hence rainflow counting algorithm is used to analyze it. The following parameters are extracted for both conventional and proposed switch.



(a) Rainflow Matrix with Si-IGBT



(b) Rainflow Matrix with Si- SiC IGBT

Figure 14. RF analysis

- No.of Cycles N_i,
- Mean Junction Temperature T_{jm},
- Cycle Amplitude ΔT.

The corresponding rainflow histogram is presented in figure 14.

5.2.4 MCS analysis and B_{10} lifetime calculation:

Based on the parameters of RF analysis, Monte Carlo simulation is implemented to calculate the B_{10} lifetime. The population size of 10000 with 5 % variation is considered. Component level and system level B_{10} lifetime curve are plotted for both conventional and proposed switch as shown in figure 15.

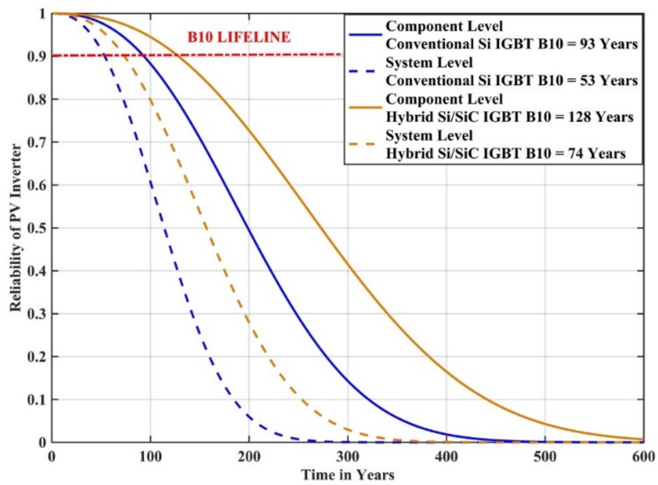


Figure 15. B_{10} lifetime curves

The B_{10} lifetime is improved with proposed switch at both component level and system level. At component level B_{10} lifetime is improved from 93 years to 128 years. Similarly, at system level B_{10} lifetime is improved from 53 years to 74 years.

5. CONCLUSIONS

In this paper Hybrid Silicon-Silicon Carbide IGBT for Photo Voltaic Applications is proposed. Mission profile oriented reliability assessment is carried out on the proposed Hybrid Silicon-Silicon Carbide IGBT at two different atmospheric conditions. One is hot atmospheric conditions i.e. India and the other is cold atmospheric condition i.e. Denmark. Solar Irradiance and Ambient Temperature with one-minute resolution for one year from Sep'18 to Aug'19 is considered as mission profile. Foster Electro Thermal model is considered to extract the junction temperature from the logged mission profile. Rainflow analysis is implemented to analyze the extracted junction temperature. Monte Carlo simulation is implemented to calculate the B_{10} lifetime at component level and system level. The population size of 10000 with 5 % variation is considered. The B_{10} lifetime is improved with proposed switch at both India and Denmark locations.

REFERENCES

[1] C. Liu et al., "Hybrid SiC-Si DC–AC Topology: SHEPWM Si-IGBT Master Unit Handling High Power Integrated with Partial-Power SiC-MOSFET Slave Unit Improving Performance," in IEEE Transactions on Power Electronics, vol. 37, no. 3, pp. 3085-3098, March 2022, doi: 10.1109/TPEL.2021.3114322.

[2] R. A. Minamisawa, U. Vemulapati, A. Mihaila, C. Papadopoulos and M. Rahimo, "Current Sharing Behavior in Si IGBT and SiC MOSFET Cross-Switch Hybrid," in IEEE Electron Device Letters, vol. 37, no. 9, pp. 1178-1180, Sept. 2016. doi: 10.1109/LED.2016.2596302.

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

[4] M. Rahimo et al., "Characterization of a Silicon IGBT and Silicon Carbide MOSFET Cross-Switch Hybrid," in IEEE Transactions on Power Electronics, vol. 30, no. 9, pp. 4638-4642, Sept. 2015. doi: 10.1109/TPEL.2015.2402595.

[5] G. Wang, F. Wang, G. Magai, Y. Lei, A. Huang and M. Das, "Performance comparison of 1200V 100A SiC MOSFET and 1200V 100A silicon IGBT," 2013 IEEE Energy Conversion Congress and Exposition, Denver, CO, USA, 2013, pp. 3230-3234, doi: 10.1109/ECCE.2013.6647124.

[6] S. Hazra et al., "High Switching Performance of 1700-V, 50-A SiC Power MOSFET Over Si IGBT/BiMOSFET for Advanced Power Conversion Applications," in IEEE Transactions on Power Electronics, vol. 31, no. 7, pp. 4742-4754, July 2016, doi: 10.1109/TPEL.2015.2432012.

[7] H. Mirzaee, A. De, A. Tripathi and S. Bhattacharya, "Design Comparison of High-Power Medium-Voltage Converters Based on a 6.5-kV Si-IGBT/Si-PiN Diode, a 6.5-kV Si-IGBT/SiC-JBS Diode, and a 10-kV SiC-MOSFET/SiC-JBS Diode," in IEEE Transactions on Industry Applications, vol. 50, no. 4, pp. 2728-2740, July-Aug. 2014, doi: 10.1109/TIA.2014.2301865.

[8] Duong et al., "Comparison of 4.5 kV SiC JBS and Si PiN diodes for 4.5 kV Si IGBT anti-parallel diode applications", Proc. 26th Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC), pp. 1057-1063, Mar. 2011. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=907368 (Accessed March 31, 2023).

[9] S. Rugen, C. Bödeker, I. Kortazar, I. Larrazabal, P. Friedrichs and N. Kaminski, "Investigation of the turn-on behaviour of silicon pin-diodes and SiC-Schottky-diodes and its impact on the anti-parallel IGBT," 2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe), Karlsruhe, Germany, 2016, pp. 1-9, doi: 10.1109/EPE.2016.7695461.

[10] Kumar, D.G.; Ganesh, A.; Sireesha, N.V.; Kshatri, S.S.; Mishra, S.; Sharma, N.K.; Bajaj, M.; Kotb, H.; Milyani, A.H.; Azhari, A.A. Performance Analysis of an Optimized Asymmetric Multilevel Inverter on Grid Connected SPV System. Energies 2022, 15, 7665. https://doi.org/10.3390/en15207665.L.

[11] R. k. Gatla, W. Chen, G. Zhu, J. V. Wang and S. S. Kshatri, "Lifetime comparison of IGBT modules in Grid-connected Multilevel PV inverters Considering Mission Profile," 2019 10th International Conference on Power Electronics and ECCE Asia (ICPE 2019 - ECCE Asia), 2019, pp. 2764-2769, doi:10.23919/ICPE2019-ECCEAsia42246.2019.8797029.

[12] Kshatri SS, Dhillon J, Mishra S, Tariq R, Sharma NK, Bajaj M, Rehman AU, Shafiq M, Choi J-G. Reliability Analysis of Bifacial PV Panel-Based Inverters Considering the Effect of Geographical Location. Energies. 2022; 15(1):170. https://doi.org/10.3390/en15010170.

[13] Gatla, R.K., Kshatri, S.S., Sridhar, P., Malleswararao, D.S., Kumar, D.G., Kumar, A.S., Lu, J.H. (2022). Impact of mission profile on reliability of grid-connected photovoltaic inverter. Journal Européen des Systèmes Automatisés, Vol. 55, No. 1, pp. 119-124. https://doi.org/10.18280/jesa.550112.

[14] S. Singh Kshatri, J. Dhillon and S. Mishra, "Impact of Panel Degradation Rate and Oversizing on PV Inverter Reliability," 2021 4th International Conference on Recent Developments in Control, Automation & Power Engineering (RDCAPE), 2021, pp. 137-141, doi:10.1109/RDCAPE52977.2021.9633585.