Comparative Analysis of Silicon Carbide and Silicon Switching Devices for Multilevel Cascaded H-Bridge Inverter Application with Battery Energy Storage

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***Abstract*—This paper investigates the use of power semiconductor devices in a nine - level cascaded H-bridge (CHB) multilevel inverter topology with an integrated battery energy storage system (BESS) for a 13.8kV medium voltage distribution system. In this topology, the bulky conventional step-up 60 Hz transformer is not used. The purpose of this study is to analyze the use of SiC MOSFET and Si IGBT devices in the inverter system to evaluate their respective performances. SiC MOSFET and Si IGBT switching devices are modeled and characterized using Saber® modeling software. The switching losses, thermal performance, and efficiency of the inverter system are investigated, and measurements are obtained from the simulation. Saber® provides a good capability for characterizing semiconductor models in the real world, with great features of computation. A three-phase SiC power MOSFET-based multilevel CHB inverter prototype is presented for experimental verification. In the investigation, better performances of SiC MOSFET devices are recorded. SiC devices demonstrate promising performance at different switching frequency and temperature ranges.**

Keywords—Cascaded H-bridge, CosmosScope Saber, Si IGBT, SiC MOSFET

I. Introduction

Modular multilevel converter (MMC) topology is a promising topology in the power electronics industry and it is used frequently in medium and high voltage applications [1], [2]. In the past, several investigations were made [3-7] on loss estimation, thermal behavior and efficiency of SiC and Si based power devices in converter applications. SiC MOSFETs show more benefits in inverter applications compared to Si IGBT. In [3], a comparative analysis of SiC and Si was performed using PSCAD and Matlab/Simulink models. A double pulse test investigation was performed for a two and three level inverter in. The focus of the investigation was on the influence of DC bus voltage on the switching losses of SiC and Si power devices [5]. The feasibility of MMC in a permanent magnet synchronous motor (PMSM) torque and speed control was investigated in [8] and was reported that Si IGBT power devices experience performance degradation when used in extreme environments. A MATLAB/Simulink based model was implemented for performance comparison. In [9], the thermal conductivity of Si IGBT was inferior to that of SiC MOSFET. As dissipated power increases to higher numbers in hundreds of watts, the cooling effort, switching transient duration and thermal cycling stress poised a limitation to using Si. Mitigating this problem will be costlier because larger heat sink will be required. The high blocking voltage capability of SiC MOSFET is also an advantage over Si IGBT

A battery energy storage system (BESS) for multilevel cascaded H-bridge is the focus for this paper. Reviewing previous literatures on works done on multilevel cascaded H-bridge inverter and the problem faced using Si devices, it is therefore important to investigate and compare the performances of SiC MOSFET and Si IGBT in BESS for multilevel CHB and then select the best choice device for the application. Since power loss is a crucial issue in inverter, it is important to carefully choose the right device. Failing to choose the right switching device will most likely result to an efficiency degradation of the inverter system. This paper compares switching losses, conduction losses, thermal performance, and efficiency of the inverter using SiC MOSFET and Si IGBT with the same power rating. A Cree SiC MOSFET C2M0040120D (1200V, 60A) and Infineon Si IGBT IKW25N120T2 (1200V, 60A) are selected for the comparative analysis. These devices were modeled in the Saber® built-in power MOSFET and IGBT tool with the aim of creating a real device model for the simulation. Several steps were involved in creating a model that fits the datasheets of these used devices. The characterized models were then used in simulation to test for convergence at different temperatures and operating frequencies. This followed the actual use of the models in the CHB inverter circuit. The power and energy losses were calculated directly from cosmosScope™ using the embedded waveform calculator tool.

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The outline of this paper follows the sequence: Section II describes the circuit topology and control for the dc-dc and dc-ac stages of conversion. Section III illustrates the methodology for modeling Si and SiC devices used for the simulation. Section IV discusses the simulation results and comparison of Si and SiC devices. Section V describes the experimental verification using a low voltage SiC-based prototype.

II. CONVERTER TOPOLOGY

The converter topology in Fig. 1 is a three phase nine-level CHB inverter with synchronous buck/boost dc-dc converter. The dc/dc converter stage is used to boost the low voltage battery bank of the storage system. It can also be seen that each phase consists of four cells. In the converter stage, the dc/dc converter is regulating the dc bus voltage as it draws energy from the battery storage connected to the converter. The output of the topology, which is a nine level CHB is 4E, 3E, 2E, E, 0, -E, -2E, -3E, and -4E. For a single phase, the output voltage V_{AN} is the summation of v_{H1} to v_{HN}, where N is the number of CHB cells. The three-phase output $V_{AB(\max)}$ is expressed using the following equation:

$$[V_{AB(\max)} = 0.612\ (m-1)\ V\_dc] \qquad (1)$$

Where: $m = 2N+1$ and N = number of cells per phase. The same converter topology is used for the comparative analysis of SiC MOSFET and Si IGBT devices.

A. Control Stages for dc-dc and dc-ac

A phase-shifted PWM is used in the CHB inverter. Phase-shifted PWM is a modulation technique that is frequently used for cascaded multilevel inverters. One reason for the frequent usage of PSPWM is that it produces an even power distribution among the CHB cells. The implementation of PSPWM modulation technique is quite simple irrespective of the number if inverter cells. Also, switching loss is minimal in using PSPWM technique as compared to level-shifted PWM technique [10]. This PSPWM technique is used in this paper for these reasons mentioned.

The control of cascaded inverters is dependent on the circuit topology. Considering the topology used in this paper, the dc-ac stage is controlled by a decoupled current control method in Fig. 2. This control technique controls the charging and

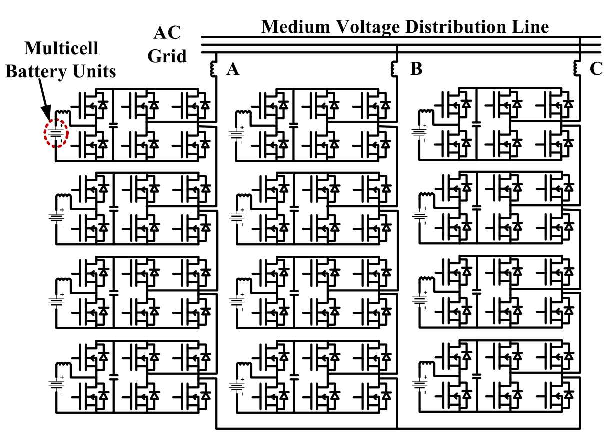

Fig. 1. MMC – CHB topology

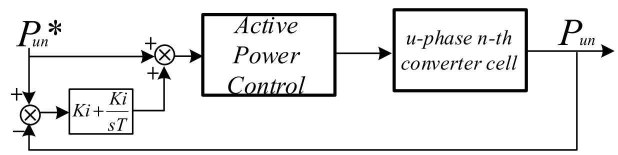

Fig. 2. Active power control

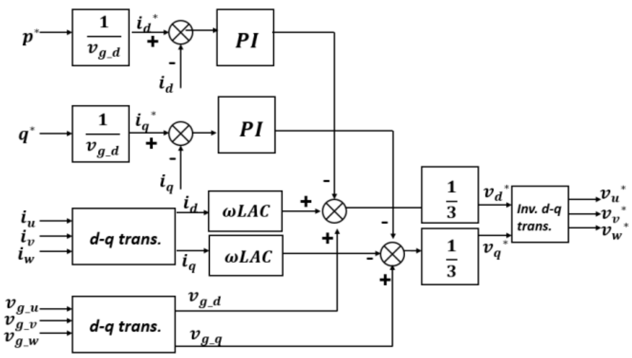

Fig. 3. Decoupled current control

discharging of batteries in the system. A lead acid battery technology is used in this work. During charging, the current is fed into the batteries from the grid, while the discharging process feeds power to the grid. In the dc-dc side, the high gain dc-dc converter adds an advantage to the system by regulating and balancing the dc bus for each cell [11]. The battery units can charge and discharge at different power levels, and at the same time produces a balanced three-phase line-to-line voltage. This is achieved because of the active-power controller [12] shown in Fig. 3 where $\boldsymbol{P^*_{un}} = \boldsymbol{P^*_{vn}} = \boldsymbol{P^*_{wn}}$ and they represent the active power commands for phases A, B, and C respectively. The investigation focuses on the primary controls for comparing Si IGBT and SiC MOSFET in the inverter. The secondary and tertiary controls are out of the scope of this paper, and are not mentioned.

III. MODELLING OF SIC MOSFET AND SI IGBT

The power MOSFET and IGBT characterization tools in Saber® model architecture was used to create and characterize compact models from datasheets prior to running simulations. The models were characterized at different temperatures, with the option to simulate the electro-thermal coupling dynamically. The characterized model plots and datasheet plots of Si IGBT are compared and matched in Fig. 4 (a) and (b). Fig. 4 (c) and (d) are the turn on characteristics of Si IGBT and SiC MOSFET respectively at 500Vdc, 20A output current, and operating power of 10 kW.

IV. SIMULATION RESULTS

In the investigation, Saber® simulation software version M-2017.12 is used to run simulations for the comparative analysis of Si IGBT and SiC MOSFET. In the setup, switches Si IGBT and SiC MOSFET switches are used in the same inverter topology for comparison. The energy and power losses of both semiconductors are calculated using the following equations:

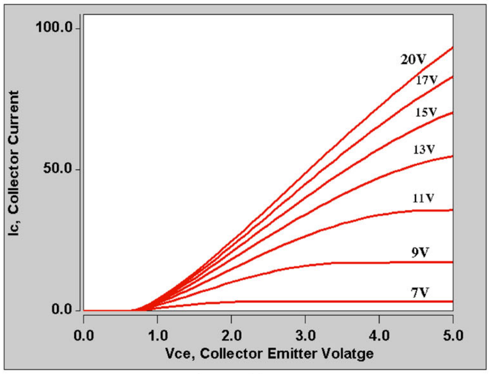

Fig. 4 (a)

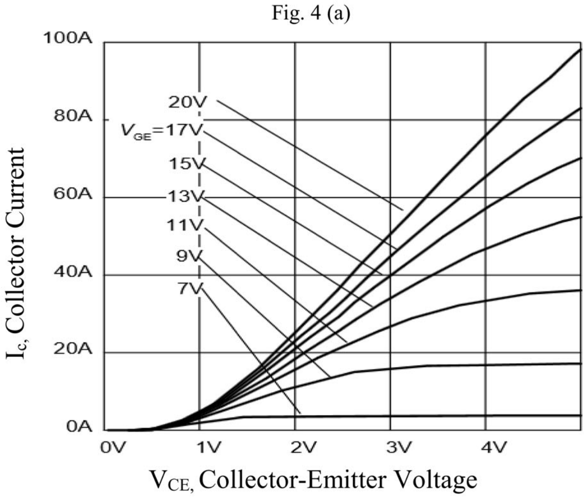

Fig. 4 (b)

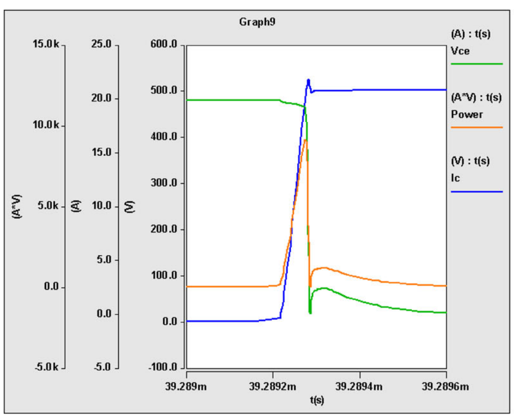

Fig. 4 (c)

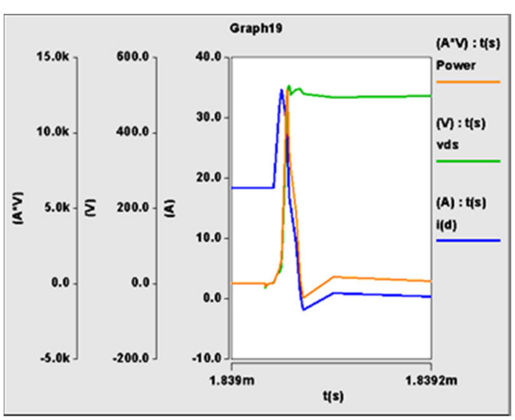

Fig. 4 (d)

Energy loss during ON time of Si IGBT and SiC MOSFET

$$E_{onIGBT} = \int_{t_1}^{t_2} i_c \, V_{ce} \, dt \quad , \; E_{onMOS} = \int_{t_1}^{t_2} i_d \, V_{ds} \, dt \quad (2)$$

Energy loss during OFF time of Si IGBT and SiC MOSFET

$$E_{offIGBT} = \int_{t_1}^{t_2} i_c \, V_{ce} \, dt \; , \; E_{offMOS} = \int_{t_1}^{t_2} i_d \, V_{ds} \, dt \quad (3)$$

where i_c and V_{ce} are the collector current and collector to emitter voltage respectively, i_d and V_{ds} are the drain current and drain to source voltage. The tool functions on the cosmosScopeTM provided the possibility to integrate and measure directly from simulated plots.

The switching losses in the MOSFET and IGBT are the products of switching energies and the switching frequency. In Fig. 5, the switching loss of an H-bridge VSI topology is observed in 2 devices. This is because S1 and S4 experience both turn-on and turn-off losses during operation. S3 and S4 do not undergo switching losses as the diodes conduct for these devices. Thus, at any time of switching, two out of the four switches in the H-bridge inverter has both turn-on and turn-off losses, hence

$$P_{sw} = \frac{N}{2} \cdot f_s \cdot \; E_T \quad (4)$$

N represents the total number of switches in the H-bridge, f_s is the switching frequency, and E_T is the total energy loss.

The power losses in the switch is the sum of conduction and switching losses:

$$P_{loss} = P_{cond} + P_{sw} = R_{DSon} \times I_{rms}^2 + (E_{on} + E_{off}) \times f_{sw} \quad (5)$$

Switching losses of power semiconductors cannot be computed with absolute accuracy. However, knowing the ON-state and OFF-state switching of semiconductors can provide calculations to the nearest accuracy.

Table I and Fig. 6 show comparisons of SiC power MOSFET (C2M0040120D) and Si IGBT (IKW25N120T2) with the same current and voltage ratings. These devices are of the same generation. The circuitry has as input voltage of 500 Vdc and output current of 20 amps. The operation power is at approximately 10 kilowatts. In Fig. 6, SiC MOSFET shows significantly lower losses compared to Si IGBT. Selected switching frequencies of 1, 3, 6 and 10 kHz were considered for the investigation.

Table II is the efficiency data with respect to the input power of the converter. The input dc bus voltage was varied at 100V, 500V, and 700V with a switching frequency of 3 kHz. For one single period of the output waveform, the instantaneous voltage

TABLE I. ENERGY LOSSES AT TEMPERATURES OF 25°C AND 150°C
Cree SiC MOSFET-C2M0040120D and Infineon Si IGBT-IKW25N120T2

	Eon (mJ)				Eoff (mJ)			
Frequency	*T = 25°C*		*T = 150°C*		*T = 25°C*		*T = 150°C*	
(kHz)	*SiC MOSFET*	*Si IGBT*	*SiC MOSFET*	*Si IGBT*	*SiC MOSFET*	*Si IGBT*	*SiC MOSFET*	*Si IGBT*
1	0.18	0.23	0.23	0.26	0.11	0.259	0.12	0.49
3	0.116	0.225	0.21	0.26	0.144	0.24	0.178	0.26
6	0.121	0.24	0.14	0.27	0.165	0.25	0.28	0.28
10	0.12	0.28	0.142	0.3	0.16	0.3	0.192	0.393

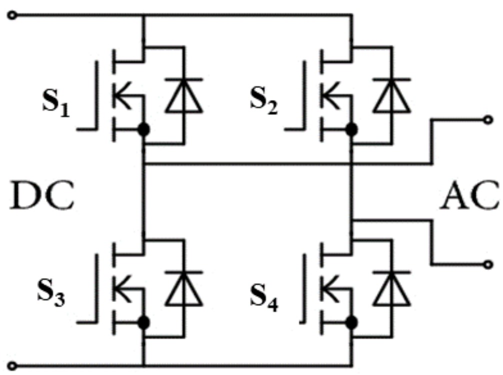

Fig. 5. Voltage source H-bridge inverter

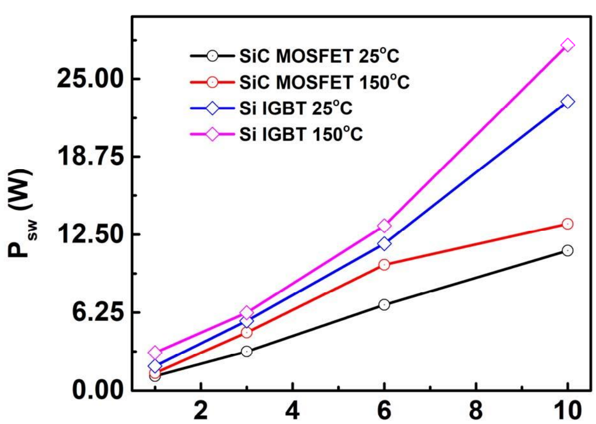

Fig. 6. Switching losses of MOSFET and IGBT

and the current through the switches were plotted. The cumulative energy in the switches and the input energy delivered from the dc side were calculated for the efficiency of the inverter. It is observed that as the input power increase the efficiency also increases.

TABLE II. EFFICIENCY VS. INPUT POWER AT 3 kHz SWITCHING FREQUENCY

	Input Voltage					
	100 V		*500 V*		*700 V*	
	SiC MOSFET	*Si IGBT*	*SiC MOSFET*	*Si IGBT*	*SiC MOSFET*	*Si IGBT*
Eff. (%)	97.74	95.25	97.76	96.86	97.92	97.01

Comparing Si IGBT and SiC MOSFET in this regard, SiC MOSFET has a higher efficiency at all power levels measured. It can also be seen from table III that SiC has shorter switching transient times compared to Si IGBT which accounts for its lower switching loss as well.

TABLE III. RISE AND FALL TIME OF SWITCHING DEVICES

	Switching frequency at 3 kHz			
	T = 25°C		*T = 150°C*	
	SiC MOSFET	*Si IGBT*	*SiC MOSFET*	*Si IGBT*
Rise time (ns)	7.72	13.29	5.35	11.17
Fall time (ns)	5.93	29.8	10.66	27.96

V. EXPERIMENTAL VERIFICATION AND PROTOTYPE

Fig. 7 is a low voltage prototype used for the experimental verification and proof of concept of the BESS in a cascaded H-bridge inverter. The prototype is SiC MOSFET-based, and scales up to 240V rms. A Cree 1200V SiC discrete device with part number CMF20120 was used in the experimental verification. The SiC-based prototype was built as a result of the observed better performances of SiC MOSFET device from the simulation, and the tremendous work done on Si-based CHB as well documented in literature. Fig 8 shows the output voltage of the CHB inverter with a 12 V battery bank.

Fig. 7. Low voltage experimental prototype

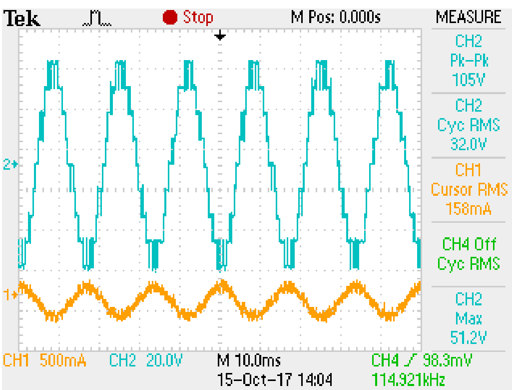

Fig. 8. Output voltage of CHB inverter

VI. CONCLUSION

This work presents a topology for modular multilevel cascaded H-bridge inverter. The inverter is analyzed using Si IGBT and SiC MOSFET switching devices which were characterized using Saber®. A loss comparison is performed to identify the most suitable switching device for the operation. SiC MOSFET shows better device performances in terms of switching loss, transient time and efficiency compared to similarly rated Si IGBT. The various temperatures and switching frequency level results obtained also show better performance with SiC MOSFET. With these results, SiC MOSFETs are a better recommendation for this topology. Since most BESS inverter systems are current controlled, SiC MOSFET devices are a better choice because of lower on-resistance (Rds-ON), lower conduction losses compared to Si IGBT, especially for megawatts power scale. Also, future work targets an RMS voltage of 13.8 kV, using novel 10 kV SiC MOSFET.

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REFERENCES

[1] Y. Zhong, N. Roscoe, D. Holliday, T. C. Lim and S. J. Finney, "High-Efficiency MOSFET-based MMC Design for LVDC Distribution Systems," in IEEE Transactions on Industry Applications, vol. PP, no. 99, pp. 1-1.

[2] Yaqiang Han et al., "A 4000V input auxiliary power supply with series connected SiC MOSFETs for MMC-based HVDC system," 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), Hefei, 2016, pp. 279-284.

[3] Hsin-Ju Chen, G. L. Kusic and G. F. Reed, "Comparative PSCAD and Matlab/Simulink simulation models of power losses for SiC MOSFET and Si IGBT devices," 2012 IEEE Power and Energy Conference at Illinois, Champaign, IL, 2012, pp. 1-5.

[4] A. Albanna, A. Malburg, M. Anwar, A. Guta and N. Tiwari, "Performance comparison and device analysis Between Si IGBT and SiC MOSFET," 2016 IEEE Transportation Electrification Conference and Expo (ITEC), Dearborn, MI, 2016, pp. 1-6.

[5] D. Oustad, M. Ameziani, D. Lhotellier, S. Lefebvre and M. Petit, "Estimation of the Losses in Si and SiC Power Modules for Automotive Applications," *PCIM Europe 2017; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, Nuremberg, Germany, 2017, pp. 1-8.

[6] R. Barrera-Cardenas, T. Isobe and M. Molinas, "Comparative study of semiconductor devices based on a meta-parameterised approach: SiC MOSFET vs Si IGBT technologies," *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, Hefei, 2016, pp. 3384-3391

[7] A. Bolotnikov *et al.*, "Overview of 1.2kV – 2.2kV SiC MOSFETs targeted for industrial power conversion applications," *2015 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Charlotte, NC, 2015, pp. 2445-2452.

[8] M. F. Rahman, P. Niknejad and M. R. Barzegaran, "Comparing the performance of Si IGBT and SiC MOSFET switches in modular multilevel converters for medium voltage PMSM speed control," *2018 IEEE Texas Power and Energy Conference (TPEC)*, College Station, TX, 2018, pp. 1-6.

[9] N. Hildebrandt, M. Petković and D. Dujić, "Evaluation of 1.7 kV SiC MOSFETs for a regenerative cascaded H-bridge multilevel converter cell," *2018 IEEE International Conference on Industrial Technology (ICIT)*, Lyon, France, 2018, pp. 718-723.

[10] M. Malinowski, K. Gopakumar, J. Rodriguez and M. A. Perez, "A Survey on Cascaded Multilevel Inverters," in *IEEE Transactions on Industrial Electronics*, vol. 57, no. 7, pp. 2197-2206, July 2010.

[11] J. Umuhoza,H. Mhiesan, K. Mordi, C. Farnell and H.A. Mantooth, " A SiC-Based Power Electronics Interface for Integrating a Battery Energy Storage into the Medium (13.8 kV) Distribution System," *2018 IEEE Applied Power Electronics Conference and Exposition (APEC), San Antonio, TX, 2018*

[12] L. Maharjan, T. Yamagishi and H. Akagi, "Active-Power Control of Individual Converter Cells for a Battery Energy Storage System Based on a Multilevel Cascade PWM Converter," in *IEEE Transactions on Power Electronics*, vol. 27, no. 3, pp. 1099-1107, March 2012

[13] R. Moghe, R. P. Kandula, A. Iyer and D. Divan, "Loss comparison between SiC, hybrid Si/SiC, and Si devices in direct AC/AC converters," *2012 IEEE Energy Conversion Congress and Exposition (ECCE)*, Raleigh, NC, 2012, pp. 3848-3855.