Investigation of WBG based Power Converters used in E-Transportation

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Abstract. Nowadays, Uses for transportation are evolving in the direction of getting more electrified due to rising fuel costs and environmentally hazardous pollutants due to which The grid's need for power is increasing dramatically. As the only solution for this is to diminish the power consumption of Electric Vehicles (EV). Enhanced component efficiency can lead to improved electric vehicle performance. Wide band gap (WBG) semiconductors, in particular silicon carbide (SiC) and Gallium Nitride (GaN), are ideal candidates of choice to address the recent growing demand in both high efficiency and great power density converters about electric vehicles. Due to their the capacity to switch at a high frequency, high temperature, high voltage, reduced size and reduced conduction losses makes them superior than Si semi-conductors. WBG devices have some properties which include rapid electron mobility, high breakdown field, and big band gap low on-state resistance and capacitance, lower co-efficient of thermal expansion (CTE) and high stability. This paper includes a study on WBG devices, their properties, and the increased efficiency of power converters i.e DC-DC boost converter and single-phase full bridge inverter using LTSpice simulation tool.

1 Introduction

Power electronic converters play an important part in e-mobility. Silicon-based power converter technology has been phased out due to limitations in operation at high switching frequencies, increased on-state resistance, and low thermal conductivity. WBG devices, which have large bandgaps due to the layers between them, provide an opportunity to overcome the limitations of Si-based technology. The GaN structure's AlGaN layer, undoped layer, and buffer layers all contribute to an increase in the forbidden gap between the valency and conduction bands. The undoped layer in GaN HEMTs, also known as the two-dimensional electron plasma, functions as a conduction layer in the system. The great thermal

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conductivity of WBG devices reduces heat sink size by up to 36% when compared to Si-based converters [3]. And the large bandgap imparts a multitude of advantageous properties, including:

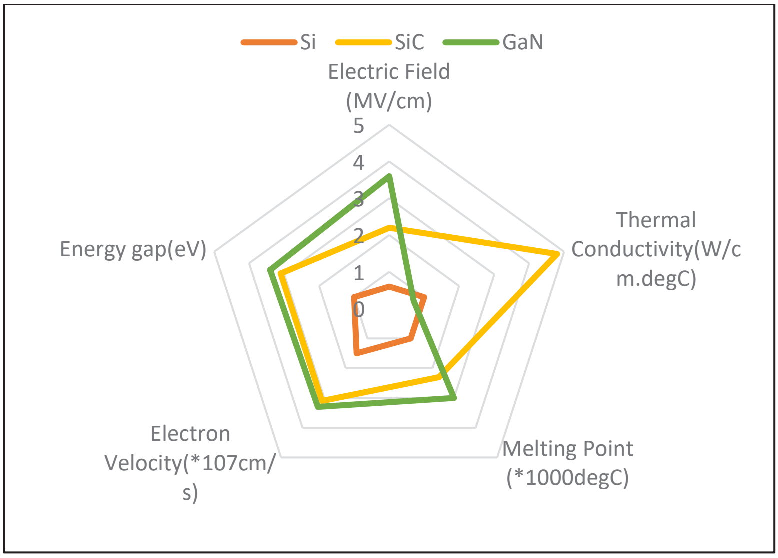

Fig. 1. Material Properties of WBG Devices

On state-resistances of WBG semiconductor devices are lower and are thinner. Higher total converter efficiency is gained since reduced Ron also translates to fewer conduction losses. WBG semiconductor devices are available at voltages lower than 300 V, but their larger electric breakdown field causes them to have higher breakdown voltages. Thermal conductivity in WBG devices is higher (4.9 W/cm-K for SiC versus 1.5 W/cmK for Si). Consequently, the junction-to-case thermal resistance, or Rth-jc, of WBG-based power devices is reduced. The temperature rises more slowly as a result of the device's easy heat transfer. Here, GaN is an exception[4].

Power devices based on semiconductors from WBG can function at high temperatures. Up to 600°C is the operating temperature of the SiC devices. However, Si devices can only function at a maximum junction temperature of 150°C.These devices can operate at high frequencies and power outputs of more than 10 KW, which is a slightly unfavourable experiment with Si-based devices because they can withstand the highest possible temperature, which reduces switching losses and electromagnetic interference (EMI) and reduces the need for or eliminates the need for sniffers [2].

2 WBG Devices in E-Transportation

There are numerous obstacles to the adoption of electric vehicles, including cost, battery pack capacity, size of power electronics, range anxiety, and inadequate charging infrastructure. One of the main challenges for these power electronic converters is to achieve high effectiveness, durability, tiny size, and minimum price. This problem is solved by using the WBG semiconductors in EV drive train.

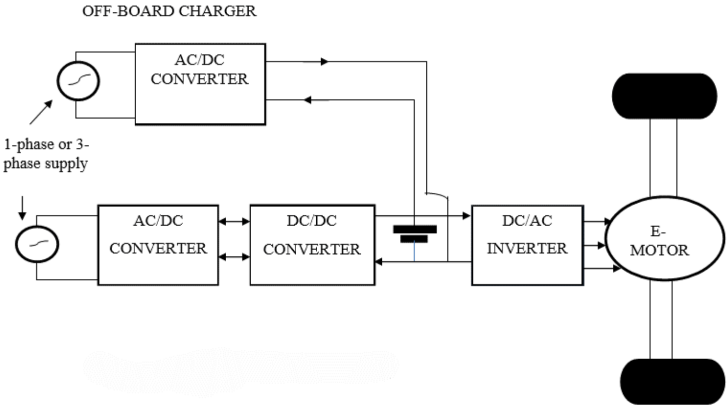

Fig. 2. Block Diagram of an EV Drive Train

2.1 WBG Devices in Charging System-

The Nissan LEAF level 3 on-board chargers and the Tesla Model S, X, Y, and 3 are both in use. In on-board chargers, cascaded AC/DC power factor correction (PFC) boost and chopper stages are employed. Because of the large switching frequency of the 650V GaN devices used in these converters, tiny storage elements (L & C) can be used in filters and the rectifiers itself. This has caused the industry to focus heavily on developing smaller converters as the need for compact converters increases.[1].In [1], a single phase dual active bridge and a bidirectional active front end (AFE) charger with an LCL grid filter are suggested. The GaN-based technology design shown benefits over the conventional Si based technology. At 500 kHz, the GaN-based charger experienced losses of 60 W, while the Si-based topology at 24 kHz experienced losses of roughly 74 W.

In [5], a bidirectional 6.6 kW on-board charger for PEVs is suggested. Both 600 V GaN and 1200 V SiC MOSFETs are employed in this OBC architecture to increase the switching frequency more than that of 300 kHz, resulting in a power density of 37 W/in3 and an efficiency of more than 96%.

It is anticipated that EVs of the future will be wirelessly charged. Electromagnetism is used to facilitate wireless charging. wide-area wireless power systems can be designed because to advancements in coil designs and the invention of robust amplifiers that use GaN MOSFETs rather than Si devices.

2.2 WBG Devices in Energy Storage Systems-

The Energy Storage Unit (ESU) in an EV is connected by a DC link between the power source and the traction drive. The Hybrid Energy Storage System (HESS) bidirectional DC/DC converter acts as an interface between the inverter and the energy storage gear. These converters' increased power density and efficiency from the usage of WBG devices allow for a smaller traction battery capacity while keeping the same range.

In [6], a bidirectional fractional buck-boost converter with a 50 Ah capacity is suggested for high power 200 V battery ESS. 100 V GaN HEMTs are used in the converter. A prototype battery system powering 1.2 kW at 100 kHz was constructed with a 99.63% peak efficiency, large power density, and reduced weight. Because of their increased efficiency, hybrid Si-

GaN systems allow for the utilisation of minimum sized power sources while yet having a higher driving range and a reduced rate of SOC depletion.

2.3 WBG Devices in Electrified Powertrains-

The requirement for this separate coolant loop may be eliminated by WBG devices' greater temperature handling capacity [7]. In [7], a Nissan LEAF-based 80 kW EV powertrain is examined. According to the results, using SiC MOSFETs in the inverter increases efficiency in the low rpm and high torque sector, significantly increasing overall efficiency for urban driving. Additionally, Toyota has developed a prototype SiC inverter for the Prius that offers better energy efficiency.

2.4 WBG Devices in Motor Drives and Auxilary Power Units (APU)-

In [5], a Si inverter and a 1 kW GaN inverter with a 150 V DC voltage of the bus are contrasted for efficiency. One-eighth of the Si inverter's losses were dispersed by the GaN inverter. The GaN inverter's effectiveness when operating at maximum capacity current and unity power factor was 99.41%, whereas the Si counterpart's was 94.52%.

Auxiliary power units (APUs) function as a mediator between the two batteries of an EV: the LV and HV batteries. An EV with several auxiliary loads requires a low-voltage electrical system and an APU with a 3 kW output power [5]. Because of the large input and output capacitors and high-frequency transformer used for power transfer, using GaN HEMTs at larger frequencies produces a system that is more power-dense.

3 Simulation Studies

3.1 Boost Converter

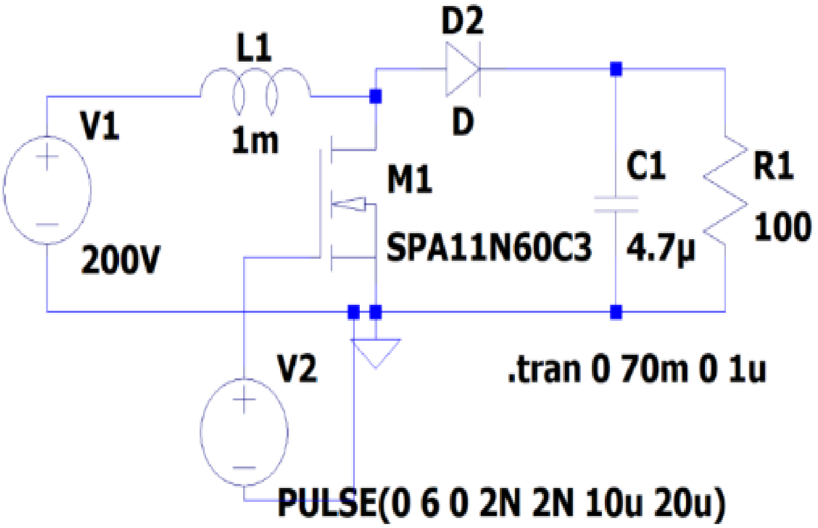

Fig. 2. Si based Boost Converter

Table.1. Parameters of Boost Converter

Parameters	**Si (SPP11N60C3)**	**GaN (GS66508P_L2V2)**
Manufacturer	Infenion	GaN Systems
V_{DS}	650v	650v
$R_{DS}(on)$	340mΩ	50mΩ
Total Gate Charge Q_G	45nC	5.8nC
I_D	11A	30A
C_{OSS}	390pF	65pF
T_R & T_F	5nsec & 5nsec	3.7nsec &5.2nsec

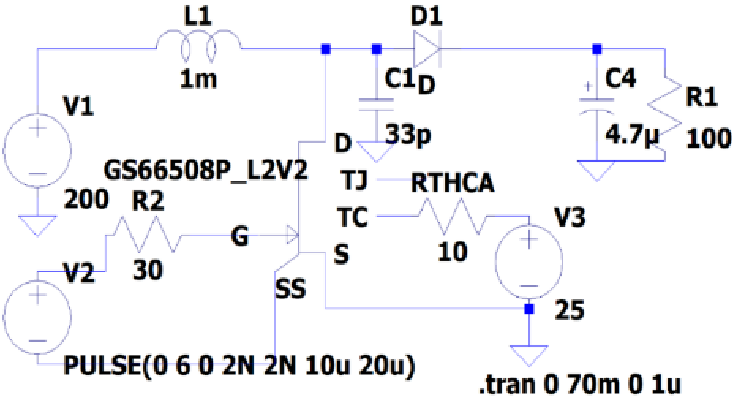

Fig. 3. GaN based Boost Converter

Fig. 2 shows the circuit diagram of a boost converter using a Si switch, and Fig. 3 shows the circuit diagram of a boost converter using a GaN switch. In a GaN-based boost converter, the enhancement GaN transistor model is used, which has two extra terminals called T_J and TC, representing the junction and case temperatures of the MOSFET. The case temperature is given as 25 using the voltage source as an equivalent temperature, and RTHCA is the thermal resistance between the case and ambient, which is given as 10 °C. PWM to the MOSFET is given through a voltage source with an amplitude of 6 volts.

Table.2. Parameters of the devices Si,GaN[9],[10]

Parameters	**Value**
Input Voltage V_{in}	200v
Output Voltage V_o	400v
Inductor	1mH
Capacitor	10μF
Output Power P_o	1.6kW
Duty Ratio D	0.5
Time Period T	20μsec
Switching Frequency f_{sw}	50kHz

Table 1 shows the power ratings of the boost converter,duty ratio to operate,the suitable inductor and capacitor Values and Table 2 shows the electrical characteristics of Si and GaN MOSFET.

https://doi.org/10.1051/e3sconf/202455201145

3.2 Simulation Results for Boost Converter

The below waveforms shows the performance of boost converter using Si and GaN MOSFETS. Fig 4 and 5 shows the characteristics of Si and GaN MOSFETS. Fig shows the output voltage and output current of Si based boost converter and Fig shows the output voltage and output current of GaN based boost converter. we can observe that the output voltage is 400v and current is 4A from the waveforms and GaN MOSFET has less settling time, rise time and ripples when compared to those of Si MOSFET. Fig 8 shows the conduction losses of Si MOSFET (27W) which are nearly 10 times greater than those of GaN MOSFET's(3W) shown in Fig 9

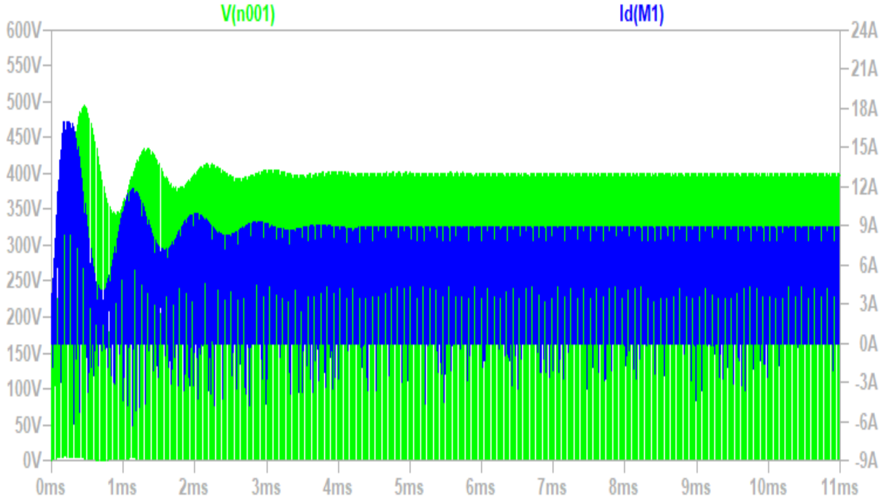

Fig. 4. Si MOSFET Voltage and Current

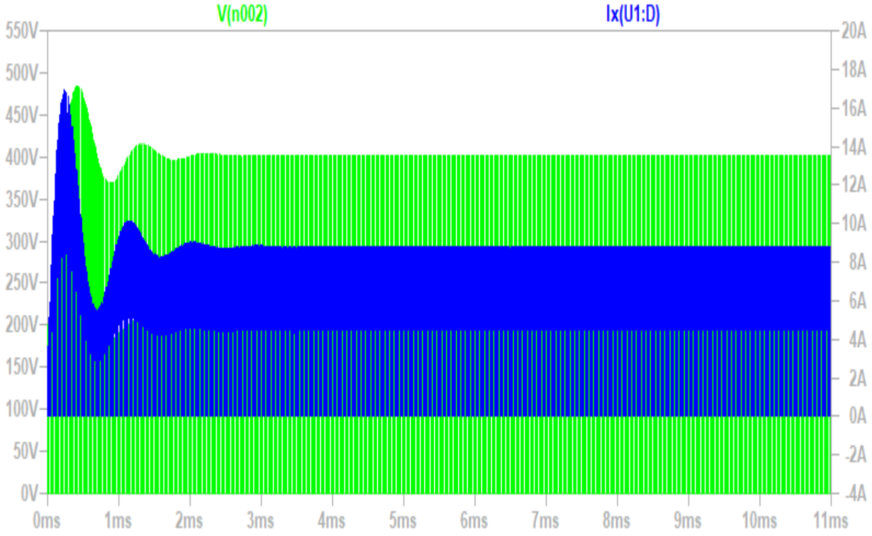

Fig.5. GaN MOSFET Voltage and Current

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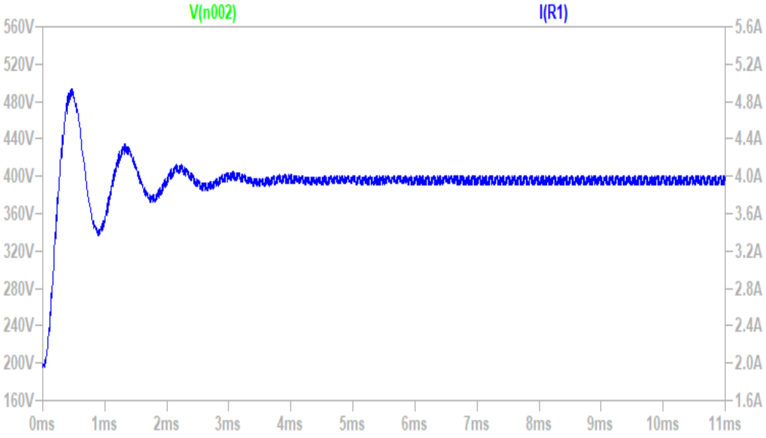

Fig. 6. Output Voltage and Current of Si based Boost Converter

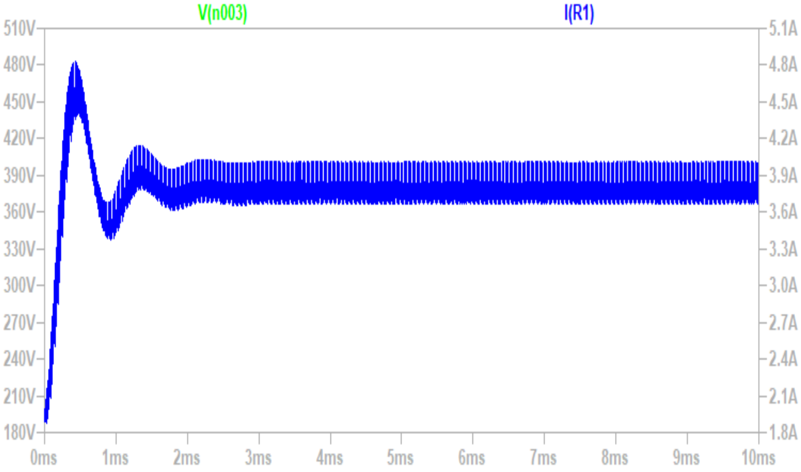

Fig.7. Output Voltage and Current of GaN based Boost Converter

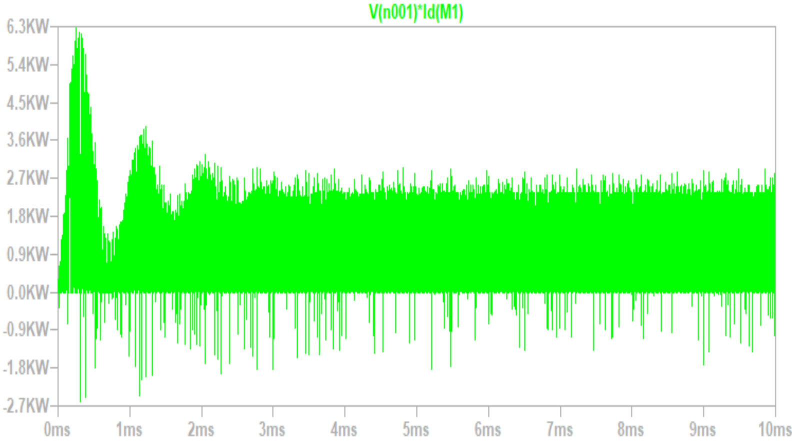

Fig. 8. Conduction losses in Si MOSFET

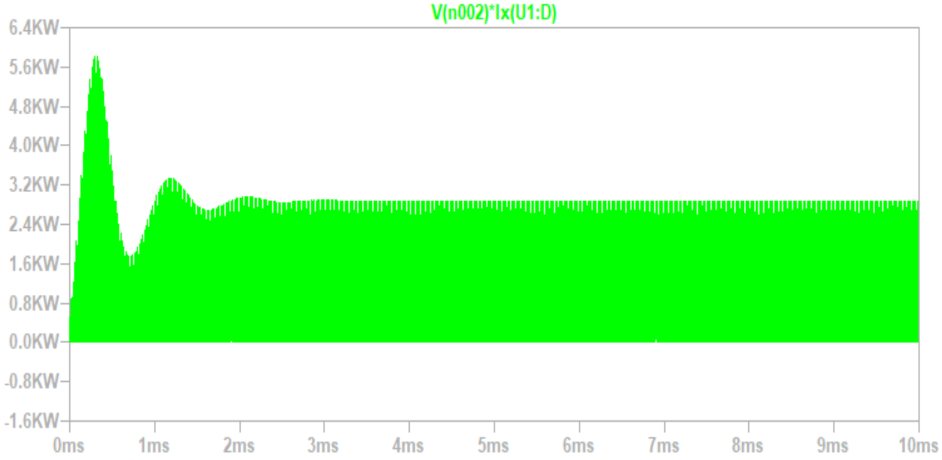

Fig. 9. Conduction losses in GaN MOSFET

3.2 Single-phase Full Bridge Inverter

Fig 18 is a simulation diagram of single-phase full bridge inverter based on Si semiconductor material(2N3055) and Fig 19 is a simulation diagram of single-phase full bridge inverter based on GaN semiconductor material (GaN_LTspice_GS66508B_L1V4P1).

3.2.1 Parameters of Si Transistor(2N3055) [11]-

V_{ceo}=60V, Collector Current I_c=15A, Base Current I_b =7A, Junction Temperature T_J=200°C,Thermal Resistance (Junction to Case) $R_{thj-case}$=1.5°C/W

3.2.2 Parameters of Enhancement mode GaNTransistor (GaN_LTspice_GS66508B_L1V4P1) [12]-

V_{DS}=650V,I_D=30A,R_{DS}=50mΩ,Q_G=5.8nC,C_{oss}=65pF, Junction Temperature T_J =-55°C to 150°C, Thermal Resistance (Junction to Case)$R_{thj-case}$=0.5°C/W

Table 3. Single-phase full bridge inverter parameters

Parameters	**Values**
Input Voltage V_{in}	50v DC
Output Voltage V_o	50v AC
Output Current I_o	120mA
Load Resistor R_l	10Ω
Load Inductor L	100mH
Time Period T	1msec
Switching Frequencyf_{sw}	1kHz

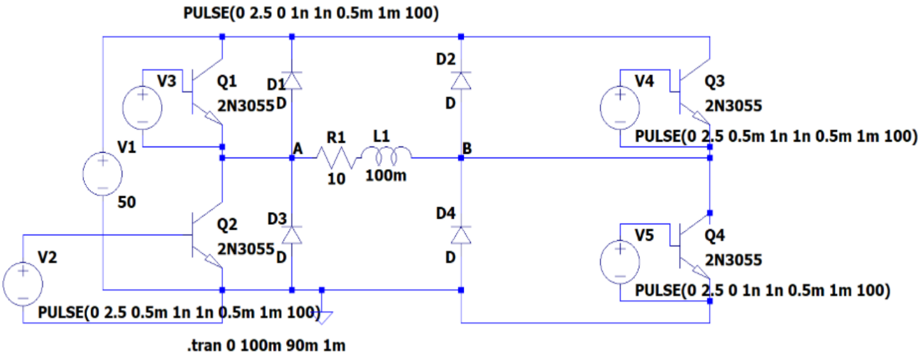

Fig. 11. GaN based Single-Phase Full Bridge Inverter

3.3 Simulation Results for single-phase full Bridge Inverter

Fig 12 & 13 shows the square waveform of output voltage which is 50V AC and triangular waveform of output current 120mA AC of single-phase FBI of Si and GaN semiconductor materials. Fig 12 shows the squared DC voltage with amplitude 50V of Si Transistor and a current of 12A.Fig 13 shows the squared DC voltage with amplitude 50V of GaN Tansistor and a current of 20A. Fig 16 shows the conduction losses of Si Transistor which are nearly 1kW i.e much greater than those of Enhancement GaN transistors 600W.Due to the decrease in conduction losses of GaN transistor the efficiency of the FBI increases significantly when compared to Si FBI.

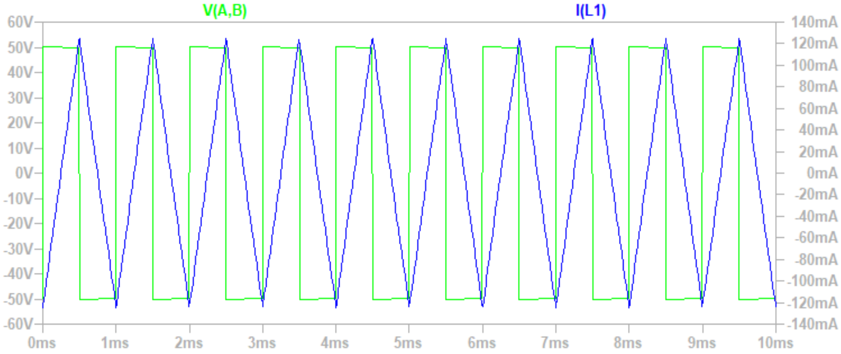

Fig. 12. Output Voltage and Output Current of Si based Single-Phase FBI

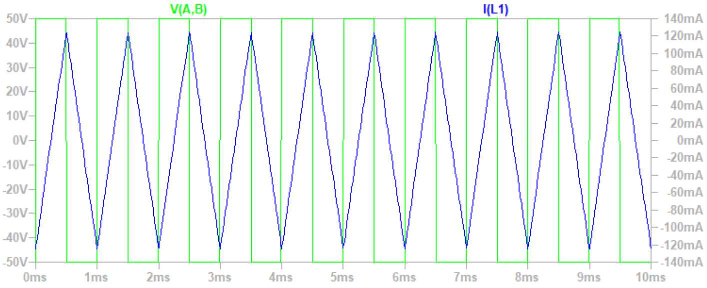

Fig. 13. Output Voltage and Output Current of GaN based Single-Phase FBI

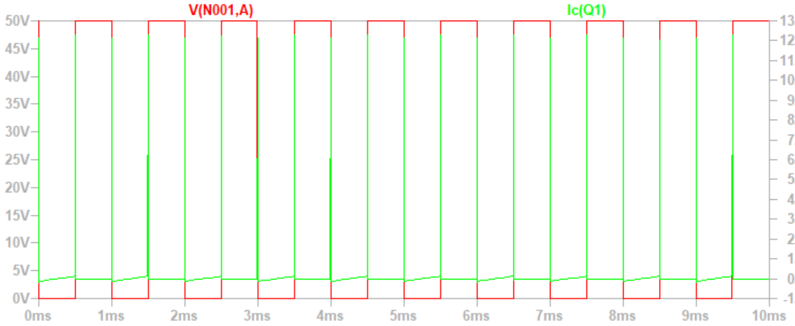

Fig. 14. Si Transistor Voltage and Current

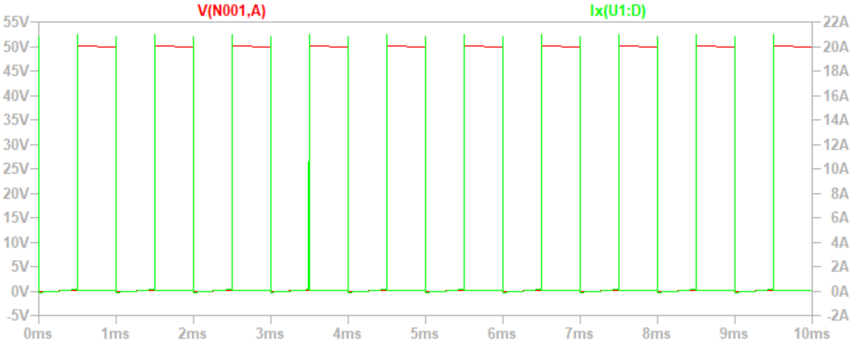

Fig. 15. GaN Transistor Voltage and Current

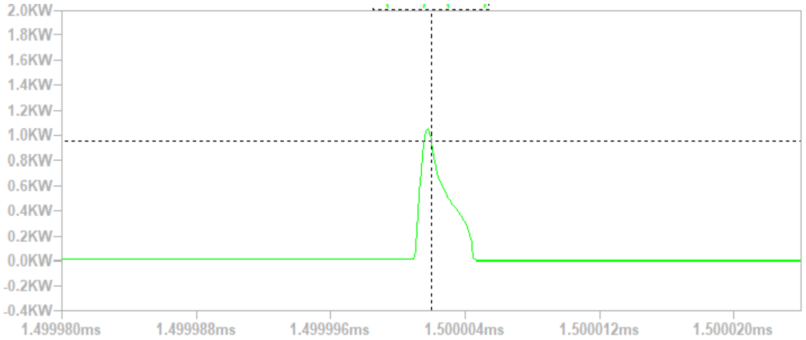

Fig. 16. Conduction losses of Si Transistor

Fig. 17. Conduction losses of GaN Transistor

4 Observations

From Table 4 we can observe that by using GaN semiconductor device there will be a decrease in conduction losses about 10% which increases the efficiency of the boost converter about 1%. And the rise time, settling time and Harmonics of the Si based boost converter are more than that of GaN based boost converter.

As we can observe from Table 5 that in FBI using GaN semiconductor device there is a change of conduction losses about 400W when compared to Si based FBI which increases the efficiency of the inverter upto 98.75%.Also the thermal resistance of GaN based FBI is much less than that of Si's which increases cooling of the inverter.

Table.4. Results from Boost Converter

Parameters	**Si based Boost Converter**	**GaN based Boost Converter**
Conduction Losses	27W	3W
Settling Time	3.5msec	2.5msec
Rise Time	0.48msec	0.45msec
Efficiency	98.31	99.81
Bandwidth	Less	More
Harmonics	More	Less

Table.5. Results from single-phase FBI

Parameters	**Si based single-phase FBI**	**GaN based single-phase FBI**
Conduction Losses	1kW	600W
Efficiency	96.45	98.75
Junction Temperature	198℃	125℃
Thermal Resistance$R_{thj-case}$	1.5℃/W	0.5℃/W

4 Conclusion

The work presented in this article focusses on e-drive train consists of DC- DC converters and Inverter. The DC-DC converter is the stage that sits in between the EV's battery and the DC link bus. Secondly, the most important converter that we use in EV's is the inverter. It transforms the battery's DC power into AC power which gives supply to the motor. We had designed a DC-DC Boost converter and single-phase full bridge inverter using Si switches and WBG switches. We observed that conduction losses, ripples, junction temperature and thermal resistance in Si based converters are more than that of WBG based converters. This made the WBG based converters to operate at higher efficiency i.e 99.81% and 98.75% with less rise time and settling time than that of Si based converters(98.31 &96.45).By using this WBG based power converters in EV drive train, the efficiency of the EV drive train increases significantly.

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