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Simulation Study of Gallium Nitride (GaN) Based Inverter for Electric Vehicle Application Using MATLAB

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Abstract: Eco-friendly has become the first consideration in developing new innovative technology in the automotive field. The fundamental change to archive the aim of eco-friendly is replacing non-renewable energy. However, when dealing with the conversion of power, the energy loss in the process is not ignorable. This paper presented a test to prove advanced semiconductors' performance in building a power device. This study aims to analyze and compare the performances of exiting advanced semiconductors like Gallium Nitride and Silicon Carbide, those semiconductors have a similarity which is wide band gap semiconductors. The experimental method to investigate the performance of those semiconductor-based inverters will be entirely based on MATLAB simulation software. The comparison aspect is based on each semiconductor-based inverter's switching and conduction loss. As a result of this thesis, the performance of Gallium Nitride dominates in lowering each loss, and by using GaN MOSFET as the material to build the inverter, the total inverter loss able reduced the loss by 22.73% compared to the inverter built by using SiC MOSFET. The study increases its accuracy by introducing different tests under various temperatures and replacing the load of the inverter with a motor model to obtain even more performance analysis information.

Keywords: Gallium Nitride, Silicon Carbide, Wide Band Gap Semiconductor, Inverter, Electric Vehicle,

1. Introduction

In the era of globalisation, eco-friendly and going green has become the primary consideration when developing new technology; due to that reason replacing non-renewable energy has become a trend, especially in a vehicle. Replacing petrol with renewable energy electricity can decrease greenhouse effect gases or have the potential to emit zero carbon dioxide CO_2 gases [1]. Two types of electric vehicles found in the market are battery and hybrid electric vehicles. It relays on the battery inside and the IC to drive the motor for battery electric vehicles. Speed changing, depends on IC or the traditional

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gear system [1]. Else the hybrid electric vehicle, as stated, is mixed up of 2 types of power systems, which is the electricity and the traditional engine; in this type of electric vehicle, with the help of electricity, it can increase the performance of the vehicle and improve the combustion of fuel inside the engine to decrease the emission of greenhouse effect gases [2].

1.1 Inverter – An important power device in an electric vehicle

An inverter is a power device to convert the DC voltage to AC voltage. In an electric vehicle, an inverter stands on an important role to drive the vehicle, since the inverter will convert the DC voltage from the battery to AC voltage to drive the motor of the vehicle. Thus, the energy loss in the inverter needs to minimize to increase the efficiency of the energy conversion.

1.2 Wide band gap semiconductor-based inverter of electric vehicle

The performance of typical semiconductors such as silicon or gallium is not enough to satisfy the need for electric vehicle performance. A high voltage source is needed to drive an electric vehicle. Although a typical semiconductor can support such a high voltage environment, it may cause much energy loss as heat and lower the efficiency of energy conversion of the inverter [3]. At this moment, the characteristic of the wide bandgap semiconductor has attracted the researcher's concentration and implemented those wide bandgap semiconductors in an inverter for the electric vehicle.

The wide band gap semiconductor such as Gallium Nitride, GaN and Silicon Carbide provided two characterises to prove the wide band gap semiconductor has a great potential in applying in an inverter. The wide energy band gap of those semiconductor provides them to operate in a high voltage operation and wide band gap semiconductor also has a high electron mobility consequence in increasing the ability to operate in high frequency [4].

2. Materials and Methods

In this section, the research methodology demonstrates the basic method to perform the project in full simulation by using MATLAB include of the formula that is used to calculate the power losses and the electrical parameter of the selected MOSFET to develop the GaN and SiC-based inverter.

2.1 The GaN and SiC MOSFET

The material of MOSFET that is used to compare the performance is the Gallium Nitrate and Silicon Carbide. The electrical characteristics of both MOSFETs are concluded in Table 1. Both specifications are under the same testing temperature, which is 25 ^{o}C. Those parameter data are taken from the GaN MOSFET and SiC MOSFET datasheet [5]-[6].

Table 1: Electrical Parameter of GaN MOSFET and SiC MOSFET

Specification	GaN MOSFET	SiC MOSFET
Drain – Source on-State Resistance $R_{DS(ON)}$	0.035 Ω	0.12 Ω
Drain Current I_{ON}	47.2 A	29 A
Turn–on switching loss $E_{m(ON)}$	44.8 μJ	61 μJ
Turn – off switching loss $E_{M(OFF)}$	54.4 μJ	41 μJ
Gate Source Voltage V_{gs}	20 V	18 V
Input Capacitance C_{iss}	1500 pF	830 pF
Reverse Transfer Capacitance C_{rss}	5 pF	1200 pF
Output Capacitance C_{oss}	147 pF	170 pF

The electrical characteristic parameter table of GaN MOSFET and SiC MOSFET shows that the GaN MOSFET has a better specification than SiC MOSET, especially on the turn on and turn off switching loss energy; this parameter is the main component in determining the switching loss of the inverter. While for the conduction loss, the main component is the drain-source on-state resistance, the GaN MOSFET has a lower resistance than SiC MOSFET, which is 35 mΩ and 120 mΩ, respectively. Thus, the result will have low conduction loss for GaN MOSFET.

2.2 Power loss formula

The main power dissipation in the inverter is from the MOSFET itself. The two types of power dissipation in the MOSFET are conduction loss and switching loss [7]. The conduction loss occurs when the MOSFET is in conduction. In contrast, the switching loss occurs when the MOSFET changes its state when it is transitioning from the off-state to the on-state to conduct electricity and vice-versa [7]. Thus, the power loss used to compare is the switching loss and the conduction loss; those losses will be depicted as heat in the inverter and affect the performance of the inverter. All the components used to calculate the switching loss and the conduction loss are taken from the datasheet of that MOSFET material. Equations 1, 2, 3 and 4 will be used to calculate the conduction and switching losses through MATLAB code [8].

$$P_{Conduction} = R_{DS(ON)} \times I_{ON}^2 \quad (1)$$

$$P_{Switching} = f_s(E_{M,ON} + E_{M,OFF}) \quad (2)$$

$$P_{TOTAL} = P_{Switching} + P_{Conduction} \quad (3)$$

$$P_{TOTAL} = 6(P_{Switching} + P_{Conduction}) \quad (4)$$

3. Results and Discussion

This results and discussion section present the comparison of simulation of the material used in this project, those selected materials are the GaN and SiC MOSFET. The GaN and SiC MOSET will be modelled using the MATLAB Simulink by extracting their electrical characteristics from the datasheet. The output and transfer characteristics obtained through the simulation and compare based on different gate voltage levels. The inverter will also model through MATLAB Simulink to observe the gate pulse of each MOSFET, the output waveform and the voltage drop of both materials. The loss calculation section will be done through the MATLAB code to calculate the conduction and switching loss of the material

3.1 Comparison of output and transfer characteristics graph of GaN and SiC MOSFET

The output characteristic graph of MOSFET shows the behaviour of drain current, I_d based on various drain-source voltage V_{ds} at the temperature condition of 25 ℃ which is the room temperature. Furthermore, the drain current I_d versus drain-source voltage is also measured through the range of 5 V to 12 V of gate voltage, V_g. Figure 1 and Figure 2 show the output characteristics of GaN and SiC MOSFET. at the gate voltage of 6 V and the drain-source voltage of approximately 4 V, the difference in drain current of both MOSFETs is 12.34 A, while at V_g = 8 V the different of drain current of both MOSFET is 49.369 A. It shows that the GaN MOSFET can archiver a high drain current than SiC MOSFET at the same drain-source voltage and gate voltage. The output characteristic graph was proved through the datasheet.

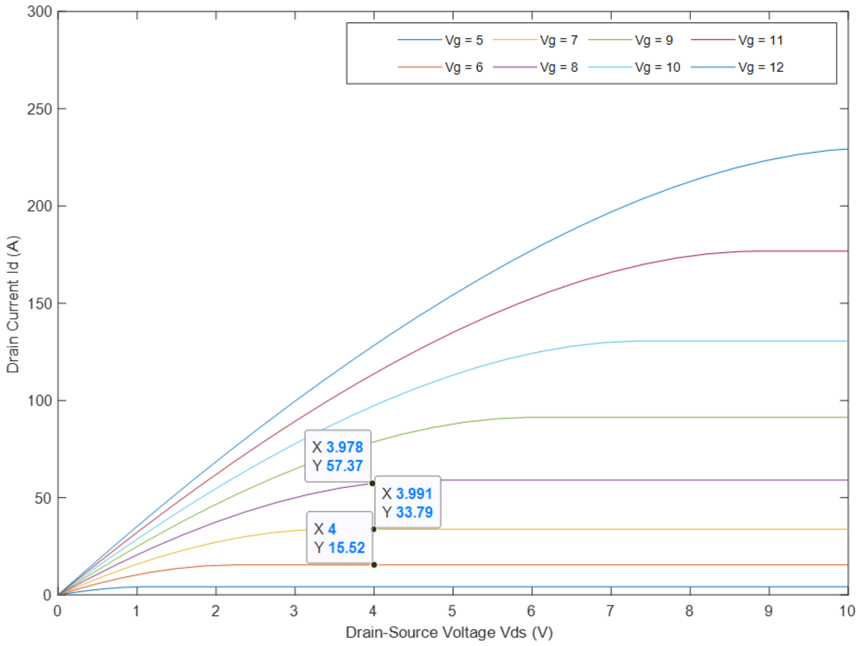

Figure 1: Output Characteristics of GaN MOSFET

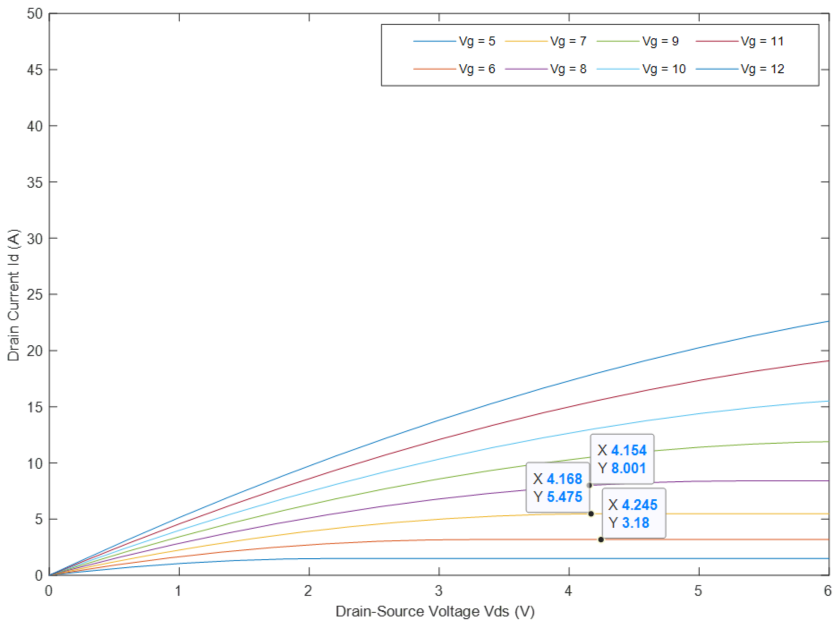

Figure 2: Output Characteristics of SiC MOSFET

The transfer characteristics of MOSFET indicate the threshold voltage of the MOSFET. When the gate voltage is over the threshold voltage the drain current will increase rapidly. Figure 3 shows that the threshold voltage of GaN MOSFET is higher than the SiC MOSFET which is 3.9 V and 2.8 V respectively. The high threshold voltage will have an advantage in resonant applications, the threshold voltage is known as the minimum voltage to turn on the MOSFET, a high threshold result in improve the switching performance by previous research [9]. Besides that, research shows by increasing the threshold voltage of a MOSFET able to increase drain current due to the increasing of electron mobility [10].

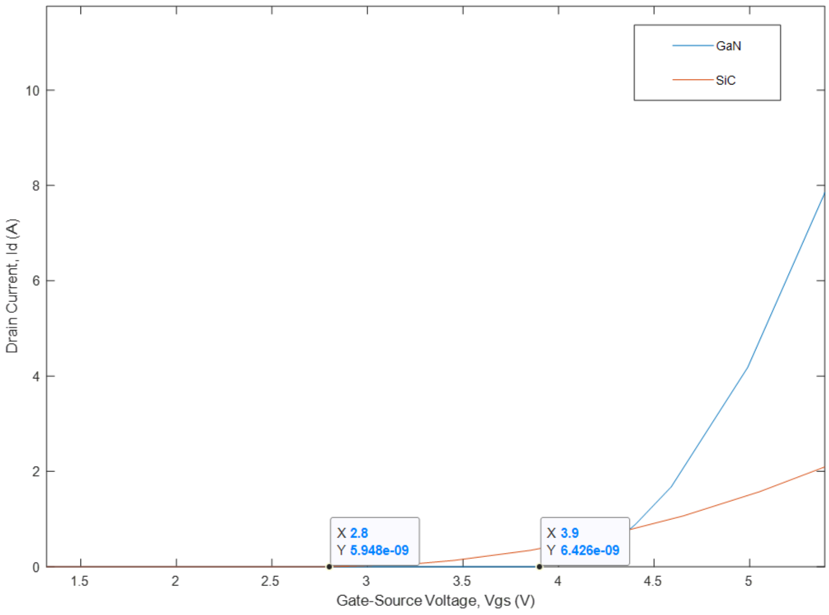

Figure 3: The threshold voltage of GaN and SiC MOSFET

3.2 Output waveform of GaN and SiC-based inverter and its gate pulse

Figure 4 shows the Simulink model of a 3-phase 180° mode inverter. The input DC voltage of the inverter is 300 V and the parameter of the MOSFET was adjusted according to the material. The gate pulse of the was generated by the signal generator, each generator had their own phase shift to convert the DC voltage to the AC 3-phase voltage. The switching frequency of this inverter is 50 Hz, and the load is the RLC series load. The pulse waveform of each signal generator was shown in Figure 5.

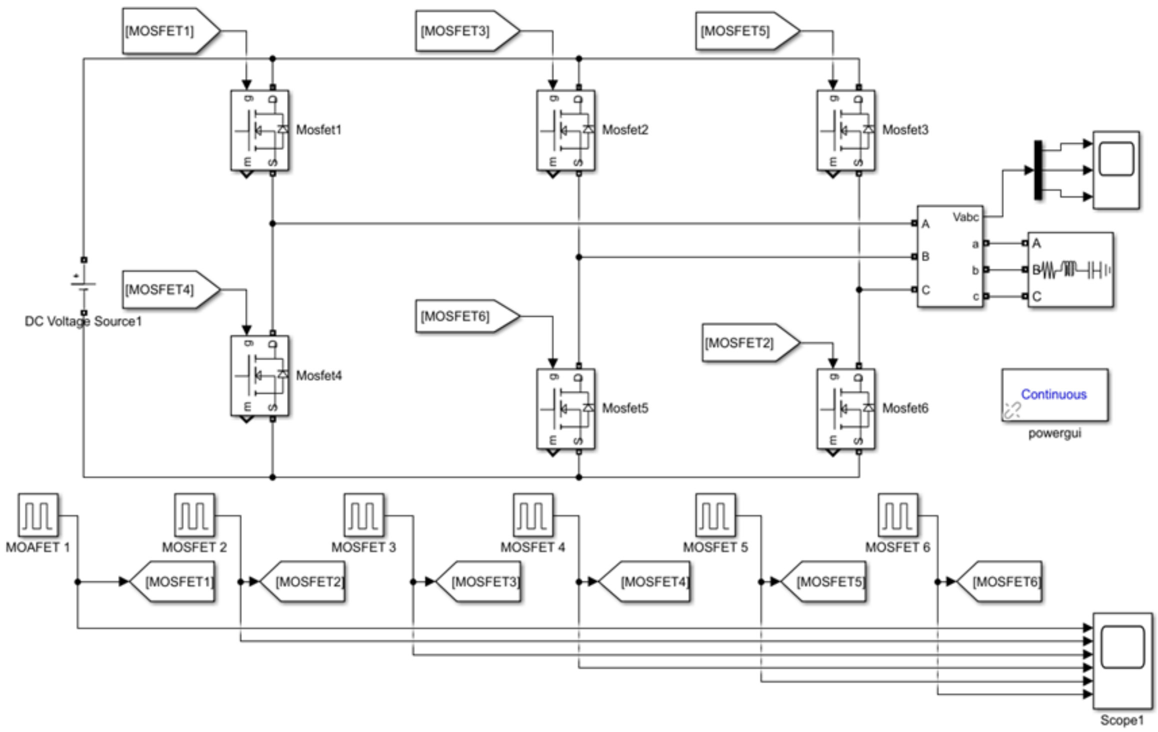

Figure 4: Simulink model of 3-phase 180° mode inverter

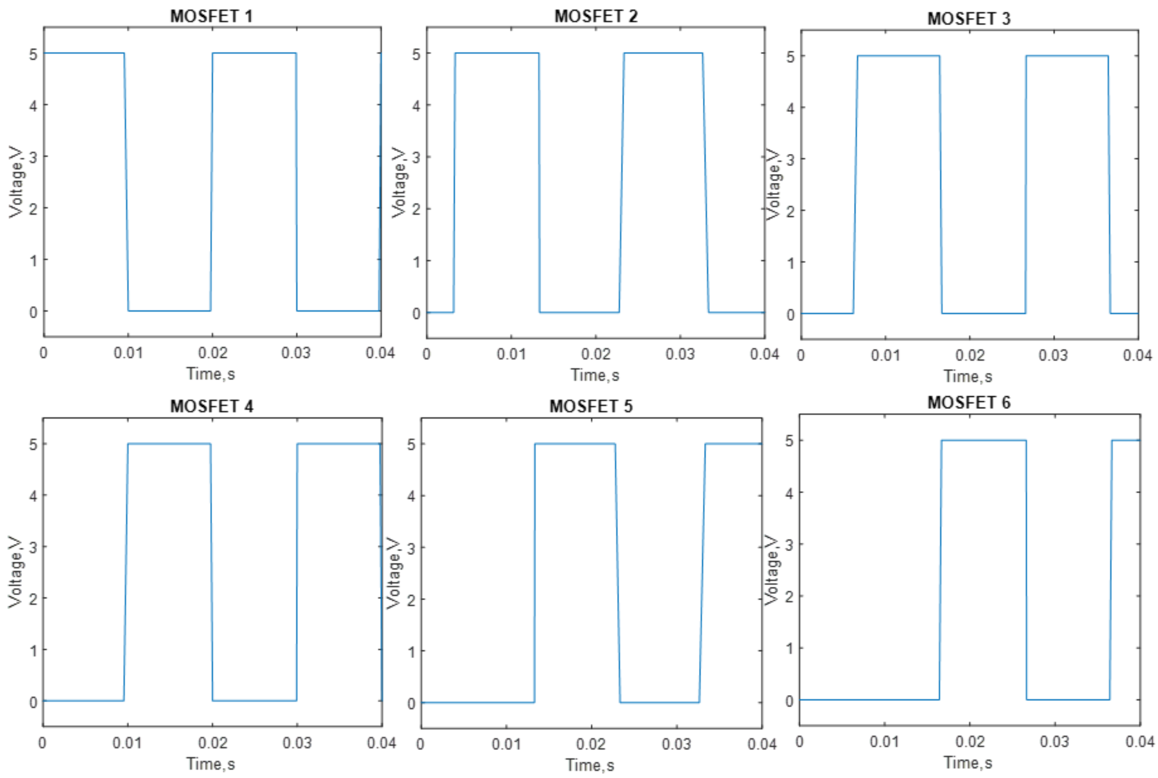

Figure 5: The gate pulse of a 3-phase 180° mode inverter

The gate pulse of MOSFET 1 and 4, 3 and 6, 2 and 5 are opposite to each other, in other words, when MOSFET 3 was switched on at the same time MOSFET will be switched off. Each gate pulse represents to the range of angle of the sinewave that can produce. MOSFET1 will generate the angle range from 0° to 60°; MOSFET2 will generate the angle range from 60° to 120°; MOSFET 3 will generate the angle range from 120° to 180°; MOSFET4 will generate the range from 180° to 240°; while MOSFET 5 will generate the range from 240° to 300°; and lastly, the MOSFET 6 will generate the range of 300° to 360°.

Figure 6 shows the 3-phase waveform is a stress case like sinewave. Which show that the inverter model successfully converted the input of 300 V DC voltage to a 3-phase AC voltage. The waveform for both materials are the same, but the different is the voltage drop.

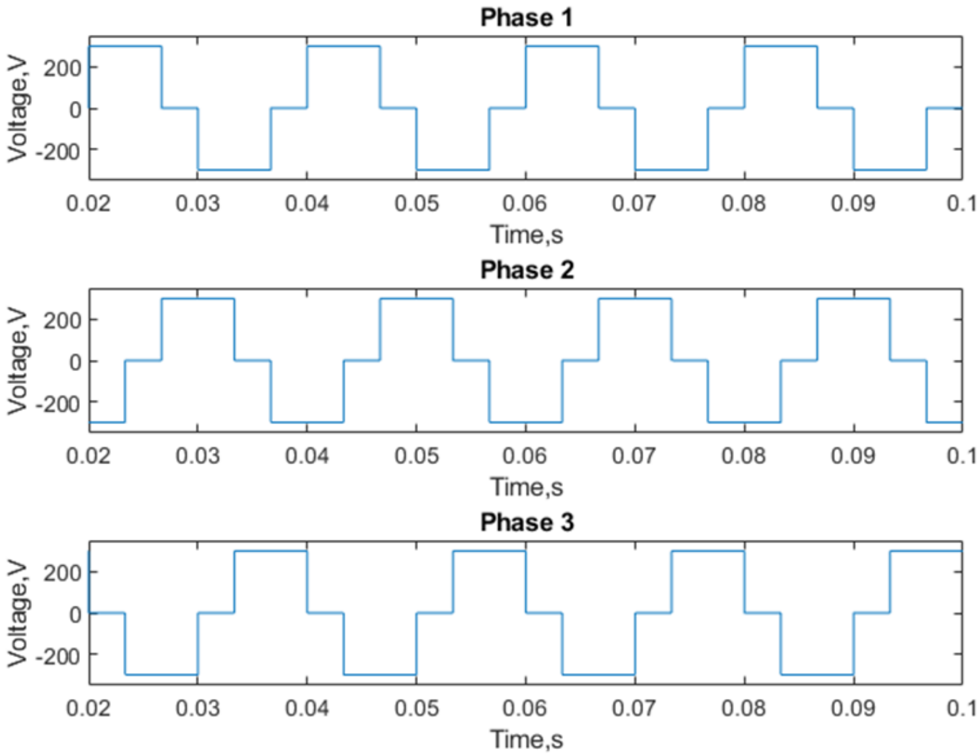

Figure 6: The output waveform of the 3-phase 180° mode inverter

Figure 7 shows the voltage drop toward different material-based inverter. For GaN-based inverter, the voltage drops from 300 V to 299.143 V (blue coloured line) while for the SiC-based inverter is 297.083 V (orange coloured line). Perhaps, both voltage drop is not significantly, but it shows that the different of voltage drop is 2.0 V and the voltage drop on SiC-based inverter is higher.

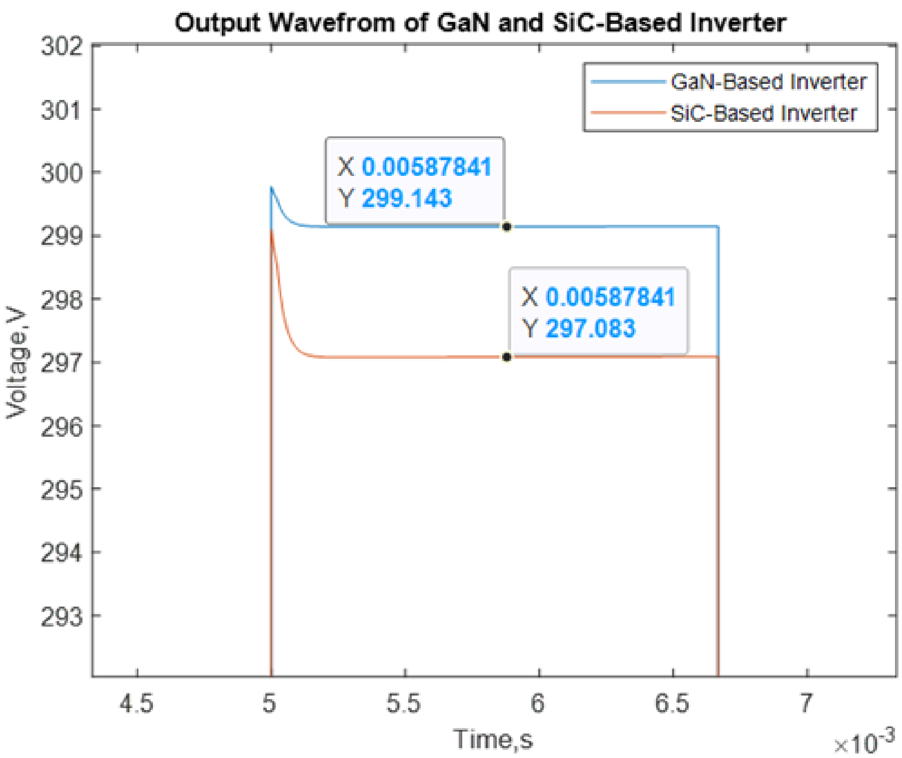

Figure 7: Output waveform peak of single phase.

3.3 Switching and conduction loss calculation of GaN and SiC-based inverter

The comparison of switching, conduction and total inverter loss between GaN and SiC-based inverters is tabulated in Table 2. Both materials are wide band gap semiconductor, while Gallium Nitride show higher performance and reduce more loss than then Silicon Carbide.

Table 2: Loss calculation of GaN and SiC-based inverter

Loss	GaN MOSFET (W)	SiC MOSFET (W)	Loss Reduction (%)
Conduction Loss	77.9744	100.9200	22.74
Switching Loss	5000µ	5100µ	1.96
Total Inverter Loss	467.8760	605.5510	22.73

Figure 8 shows the switching frequency versus total inverter loss of GaN and SiC-based inverter.

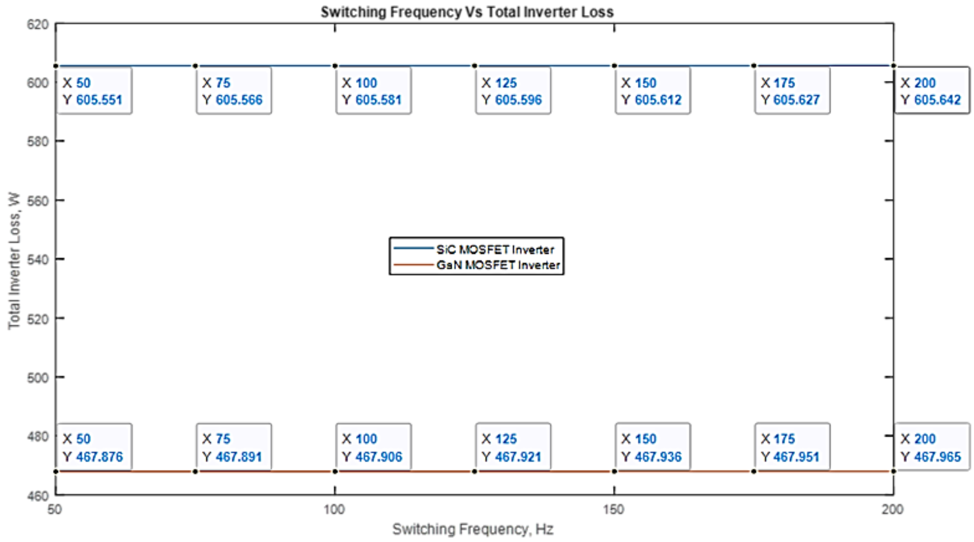

Figure 8: Switching frequency versus total inverter loss of GaN and SiC-based inverter

The conduction loss of GaN MOSFET is lower than SiC MOSFET this is due to the GaN MOSFET having a lower static drain-source on-state resistance, it able to reduce the conduction loss by 22.74%. It shows that the switching loss of both materials is very close, and the GaN MOSFET shows a slightly lower switching loss, this is because both materials are also good materials to use in the inverter for electric vehicle application, however, it shows the superiority of GaN MOSFET when the frequency increase, this is because the GaN MOSFET is also known as high-electron-mobility-transistor, this type of field-effect transistor, HEMT is designed to support high-frequency operation [4]. Using GaN MOSFET as the material of MOSFET to build the inverter can reduce the total inverter power loss by 22.73%. It shows that the GaN MOSFET has superiority in reducing the total inverter power loss of the inverter compared to SiC MOSFET. Implementing Gallium Nitrite in the electrical vehicle provides numerous benefits in reducing the losses and improving the efficacy of the conversation of energy, it tends to design a better inverter with supporting higher voltage application and higher switching frequency [11].

4. Conclusion

In conclusion, the GaN-based inverter for electric vehicle application had been proved experimentally through simulating and implementing the model of inverter in MATLAB. The simulation software MATLAB shows an outstanding platform for simulating, designing also calculating the losses of the inverter. The analysis result prove the GaN-based inverter has a higher potential in terms of reducing the switching loss when operating at a high frequency and reducing the conduction loss with a lower drain-source on-state resistance. According to the observation of losses of both inverters, the overall inverter loss of GaN-based inverter had shown a significantly lower overall inverter loss as compared to the SiC-based inverter, perhaps the Silicon Carbide, SiC also a wide band gap semiconductor as the Gallium Nitride, GaN. It is undeniable that the GaN-based inverter is able to reduce the total inverter loss by 22.73%. Throughout the simulation, the wide band gap semiconductor Gallium Nitride demonstrates its potential for application in a high technology device. To improve the sustainability of the result of this project, there are some recommendations for future work. First is the temperature-changing consideration of the inverter since the electronic device is sensitive to temperature and temperature also will affect the performance of the device. The second recommendation is the testing load of the inverter, by using the add-on extension of MATLAB Simulink it is able to simulate the running speed of a motor, by using the model of motor able to compare the revolution per minute of the motor with respect to different material of MOSFET in the inverter.

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