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Comparison of Silicon MOSFET, Silicon Carbide MOSFET and Gallium Nitride MOSFET in EV Charging Application

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Abstract

This research focuses on the comparison of Silicon MOSFET, Silicon Carbide (SiC) MOSFET, and Gallium Nitride (GaN) MOSFET in electric vehicle (EV) charging applications. The study evaluates the performance, efficiency, and overall feasibility of these semiconductor devices in the context of their implementation in EV charging systems. To tackle the limitation and enhance charging capability, ongoing research has investigated the integration of wide bandgap (WBG) semiconductors, especially SiC and GaN, into power electronics. These WBG semiconductors provide energy density and efficiency are increased, making it a promising solution for EV charging applications. Studies using simulation models developed in MATLAB/Simulink examine the efficiency, power loss, and overall performance of inverters with these semiconductor devices. The results showed that SiC and GaN MOSFETs provide performance a better than the conventional Si MOSFETs used in the industry, which is important for high- frequency operations in EV charging systems. The findings suggest that the adoption of SiC and GaN technologies can lead to more efficient EV charging solutions and reliability, highlighting the potential for improving the future state of EV infrastructure.

1. Introduction

Electric vehicles are gradually replacing conventional vehicles due to their eco-friendliness, characterised by zero harmful gas emissions. The constraint to develop highly efficient electric vehicles is further show up by the decline of non-renewable energy sources [1]. As the world's dependence on fossil fuels continues to expand, many countries are move towards more sustainable, reliable, efficient, cost-effective, and environmentally friendly energy sources [2]. Fossil fuels are a primary source of CO_2 emissions, representing a significant environmental threat. In contrast, electric vehicles are a solution due to zero CO_2 emissions. Despite these advantages, the limitations of current battery technology remain a major obstacle to the widespread adoption of electric vehicles [3].

1.1 Advancements in Wide-Bandgap Semiconductors for Enhanced EV Charging

To address the limitation of charging capability, ongoing research efforts have led to the development of an alternative to traditional silicon semiconductors, known as wide-bandgap semiconductors [4]. Wide bandgap (WBG) semiconductors represent the departure from traditional semiconductors due to their larger bandgap, which is the energy difference between the valence and conduction bands. This greater bandgap enables WBG semiconductor power devices to operate at higher voltages, temperatures, and frequencies, making them the

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preferred choice for the next generation of efficient power converter switches. Materials like Gallium Nitride (GaN) and Silicon Carbide (SiC) offer unique advantages with SiC excelling in voltage blocking, particularly in applications starting at high voltage [5].

1.2 GaN and SiC FETs: Revolutionising Power Electronics

Gallium Nitride (GaN) and Silicon Carbide (SiC) field-effect transistors (FETs) are revolutionising power electronics by delivering higher power density and efficiency when compared to traditional silicon metal-oxide semiconductor field-effect transistors (MOSFETs). Although both GaN and SiC are categorised as wide bandgap materials, they exhibit fundamental differences that make each more suitable for specific circuit topologies and applications [6].

2. Materials and Methods

This section introduces the method for performance studies and comparing products using MATLAB and Simulink. The study started with comparation MOSFET specifications. The approach includes using a reference model to understand MOSFET output and transfer characteristics, analysing the inverter drive mode, calculating power loss with specific formulae.

2.1 Specification for Si MOSFET, SiC MOSFET and GaN MOSFET

Table 1 shows electrical characteristics between Silicon [7] , Silicon Carbide [8] and Gallium Nitride [9] MOSFET under a fixed junction temperature and these parameters will be taken from different semiconductor manufacturer product's data sheets.

Table 1 *Parameter specification for Si MOSFET, SiC MOSFET and GaN MOSFET.*

Specification	Si MOSFET	SiC MOSFET	GaN MOSFET
Static drain - source on - state resistance, $R_{DS(ON)}$	160 mΩ	60 mΩ	50 mΩ
Drain current, $I_{D(ON)}$	18 A	29 A	30 A
Turn - on switching loss, $E_{M(ON)}$	260 μJ	110 μJ	47.5 μJ
Turn - off switching loss, $E_{M(OFF)}$	50 μJ	22 μJ	8 μJ
Gate source voltage, V_{gs}	30 V	19 V	10 V
Input capacitance, C_{iss}	2190 pF	1020 pF	242 pF
Reverse transfer capacitance, C_{rss}	1.3 pF	9 pF	1.5 pF
Output capacitance, C_{oss}	1450 pF	80 pF	65 pF

2.2 Loss calculation formulae

For electric vehicle (EV) applications, losses in inverters are a key issue that must be addressed [10]. The main causes of these losses are conduction and switching issues in the semiconductor devices, which include MOSFETs made of Silicon (Si), Silicon Carbide (SiC), and Gallium Nitride (GaN). Equations (1) – (4) will be employed to calculate the losses for Silicon (Si), Silicon Carbide (SiC) and Gallium Nitride (GaN) MOSFET-based inverters [11]. Equation 1 represents the calculation of total losses of a MOSFET with the sum of conduction loss and switching loss, as six MOSFET is used in the inverter model. Therefore, equation 2 is multiplied by 6 to calculate total inverter loss. Equation 3 and 4 represented the calculation of conduction loss and switching loss respectively. These equations allow for systematic and quantitative evaluation of the conduction and switching characteristics to enable a detailed comparison between Si, SiC and GaN MOSFETs.

$$\mathbf{P_{TOTAL}} = \mathbf{P_{SWITCHING}} + \mathbf{P_{CONDUCTION}} \quad (1)$$

$$\mathbf{P_{TOTAL}} = 6(\mathbf{P_{SWITCHING}} + \mathbf{P_{CONDUCTION}}) \quad (2)$$

$$\mathbf{P_{CONDUCTION}} = \mathbf{R_{DS(ON)}} \times \mathbf{I_{ON}^2} \quad (3)$$

$$\mathbf{P_{SWITCHING}} = f_s(\mathbf{E_{M,ON}} + \mathbf{E_{M,OFF}}) \quad (4)$$

3. Result and discussion

This section analysis on the performance parameters including switching and conduction losses, total inverter losses, and output and transfer characteristics of Silicon (Si), Silicon Carbide (SiC) and Gallium Nitride (GaN) MOSFET. The outputs determine the effectiveness and applicability of each type of MOSFET to electric vehicle that require high frequency switching. The performance data and simulations were carried out by using MATLAB and MATLAB Simulink under the same condition to fairly compare these semiconductor materials.

3.1 Output and transfer characteristics of Si, SiC and GaN MOSFET

The output characteristic graph of the MOSFET shows how the drain current (I_d) varies with the drain-source voltage (V_{ds}) at a standard room temperature of 25°C, and the I_d - V_{ds} relationship was observed over a range of gate voltages (V_{gs}) from 5V to 12V. Fig. 1, 2 and 3 show the output characteristics for Si, SiC, and GaN MOSFETs. These simulations were generated from consistent samples, where electrical properties were adjusted to their parameters of each material, all under the ideal room temperature conditions (25°C) and datasheet information was used to verify if these simulations this result is accurate.

From the comparison of output characteristics of Si, SiC, and GaN MOSFETs at V_{gs} = 6V. GaN MOSFETs is found to have the highest drain current of about 24.01A at a V_{ds} of 4.98V, which showed its high efficiency and suitability for high-power applications. SiC MOSFETs is shown the on voltage of the SiC MOSFETs is approximately around 17.54A at the same V_{ds}. The Si MOSFETs have the lowest drain current with 5.97A as represented by the blue curve, which makes them a little less efficient. This comparison proves that high efficiency and high-power results arise when SiC and GaN MOSFET applied.

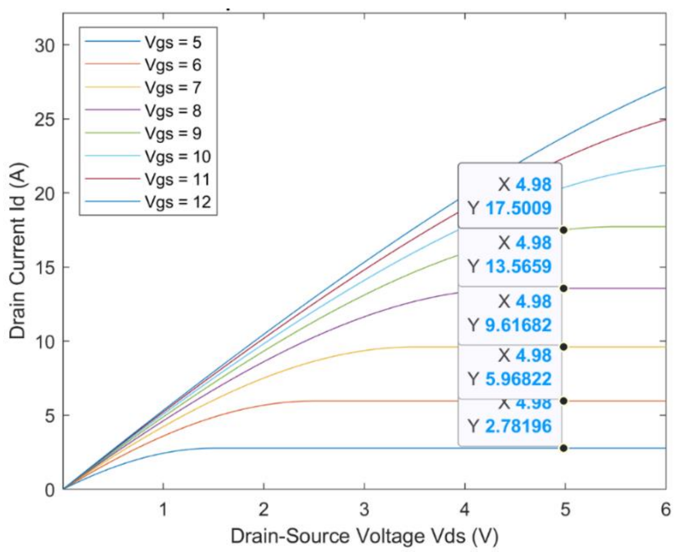

Fig. 1 *Output characteristics of Si MOSFET*

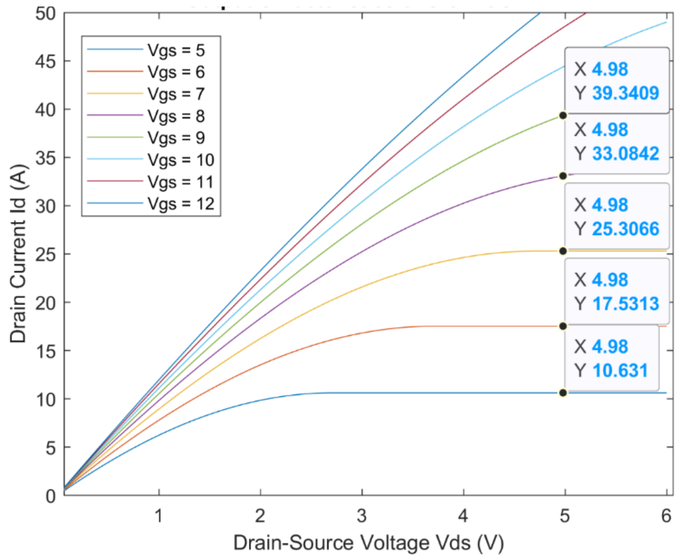

Fig. 2 *Output characteristics of SiC MOSFET*

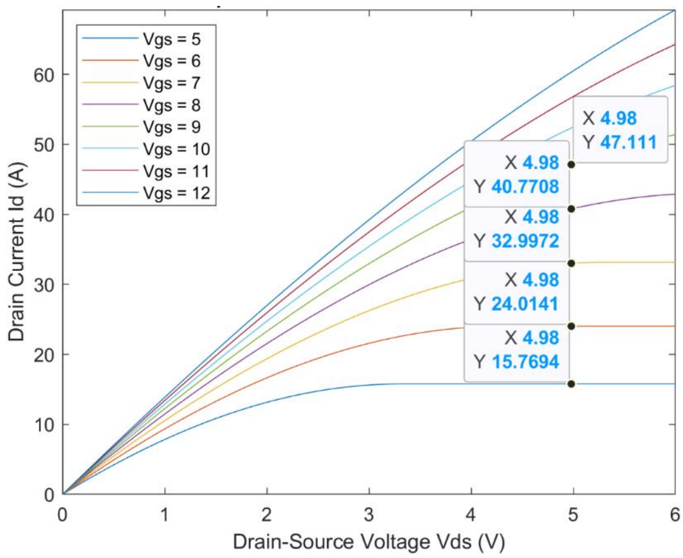

Fig. 3 *Output characteristics of GaN MOSFET*

The transfer characteristics of Si, SiC, and GaN MOSFETs are showed in Fig.4. The blue line represents the Si MOSFET, while the orange line represents the SiC MOSFET. The yellow line is the GaN MOSFET. Based on the observation from Fig.4, drain current of GaN MOSFET is increased most rapid compared to Si and SiC MOSFET.

Fig. 4 present the gate-source voltage needed in GaN, SiC, and Si MOSFETs when the drain current is about 0.0039A. The turn-on voltage of the GaN MOSFET is very low, that is 1.74V in terms of gate-source voltage. This strength is due to high electron mobility and low internal on-resistance of GaN compared to others, it is possible to apply the same current at lower voltage. On the other hand, a SiC MOSFET need a gate-source voltage of 2.34V to deliver the same drain current as the one provided in the first case. While they are more efficient than their Si MOSFET counterparts, they are slightly less efficient than their GaN MOSFET. This is because SiC gives good electron mobility but not as much as that of GaN MOSFET. Finally, the Si MOSFET also needs the largest gate-source voltage at 3.54V. One way to increase the drain current is to increase the gate voltage to achieve the same drain current. This is why the Si MOSFET has a higher voltage requirement than GaN and SiC MOSFETs because of the lower electron mobility and higher on-resistance.

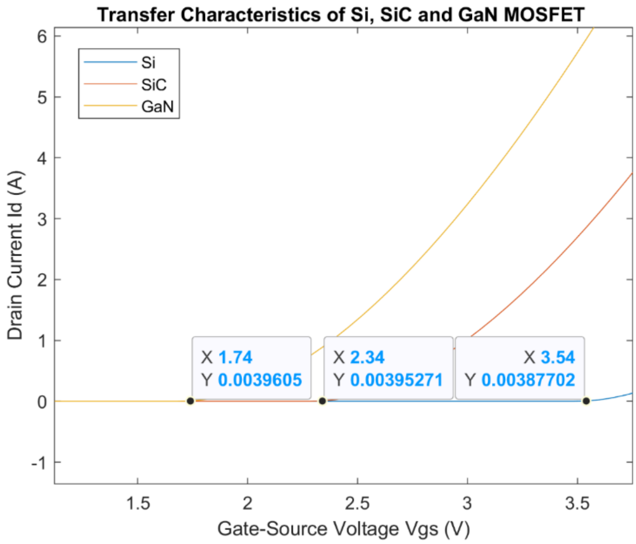

Fig. 4 *Transfer characteristics of Si, SiC, and GaN MOSFET*

3.2 Gate pulse, line voltage and phase voltage of the inverter

The inverter's Simulink model of Si, SiC, and GaN MOSFET based inverters required six MOSFET switches for the electric vehicle applications. The inverter model is shown in Fig. 5, an inverter with a switch that turns up to 180 degrees and uses a DC voltage of 300V connected to a series of RLC loads. These loads are aimed to reduce any kind of fluctuations of the inverter output current and voltage and to control the electrical current flow within the circuit. Each MOSFET switch works at pulse width of 50% of the period and a switching frequency of 50 Hz. The generated output waveforms are of two types, namely line voltage and phase voltage which assist in determining the performance of Si, SiC, and GaN MOSFETs at high voltage in the inverter.

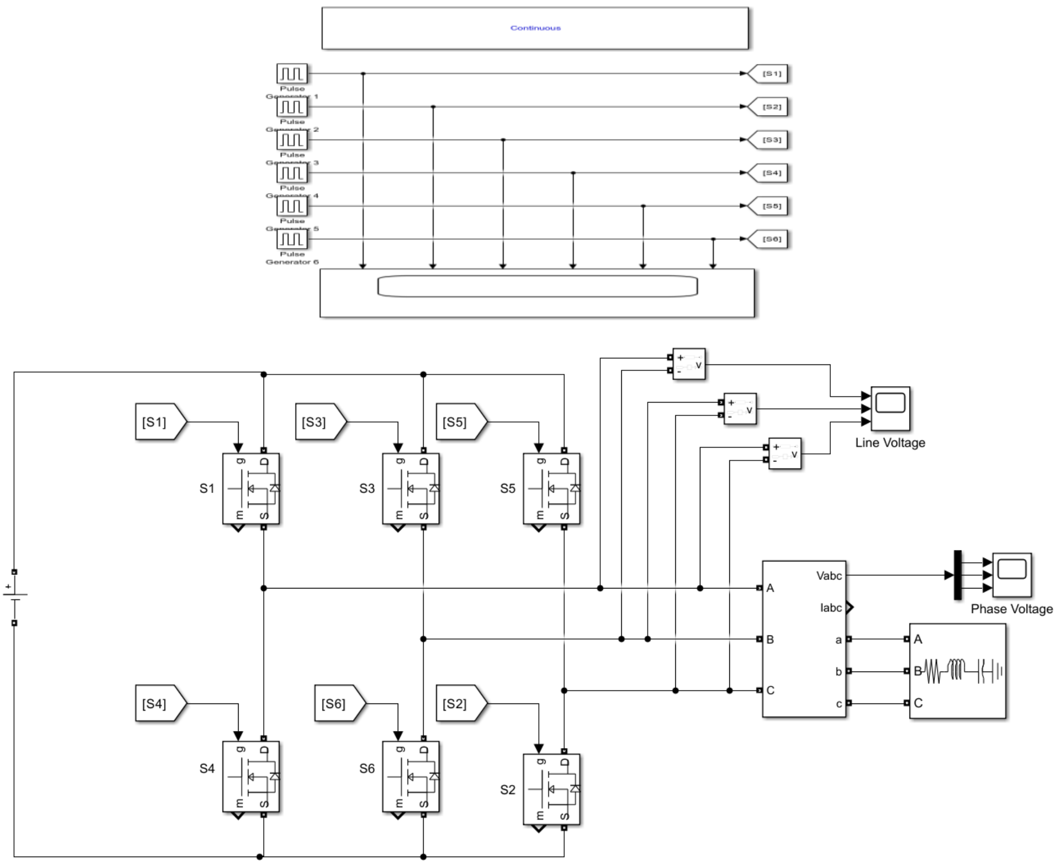

Fig. 5 *A 3-phase 180°mode inverter*

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Fig. 6 illustrates the gate pulse waveform input for each MOSFET, showing that the gate pulses of MOSFET pairs (1 and 4, 3 and 6, 2 and 5) are opposite. This means that when MOSFET-3 is switched on, MOSFET-6 is switched off, and vice versa. Each gate pulse corresponds to a specific angle range of the sine wave produced. MOSFET-1 handles the angle range from 0° to 60°, MOSFET-2 from 60° to 120°, MOSFET-3 from 120° to 180°, MOSFET-4 from 180° to 240°, MOSFET-5 from 240° to 300°, and MOSFET-6 covers the range from 300° to 360°.

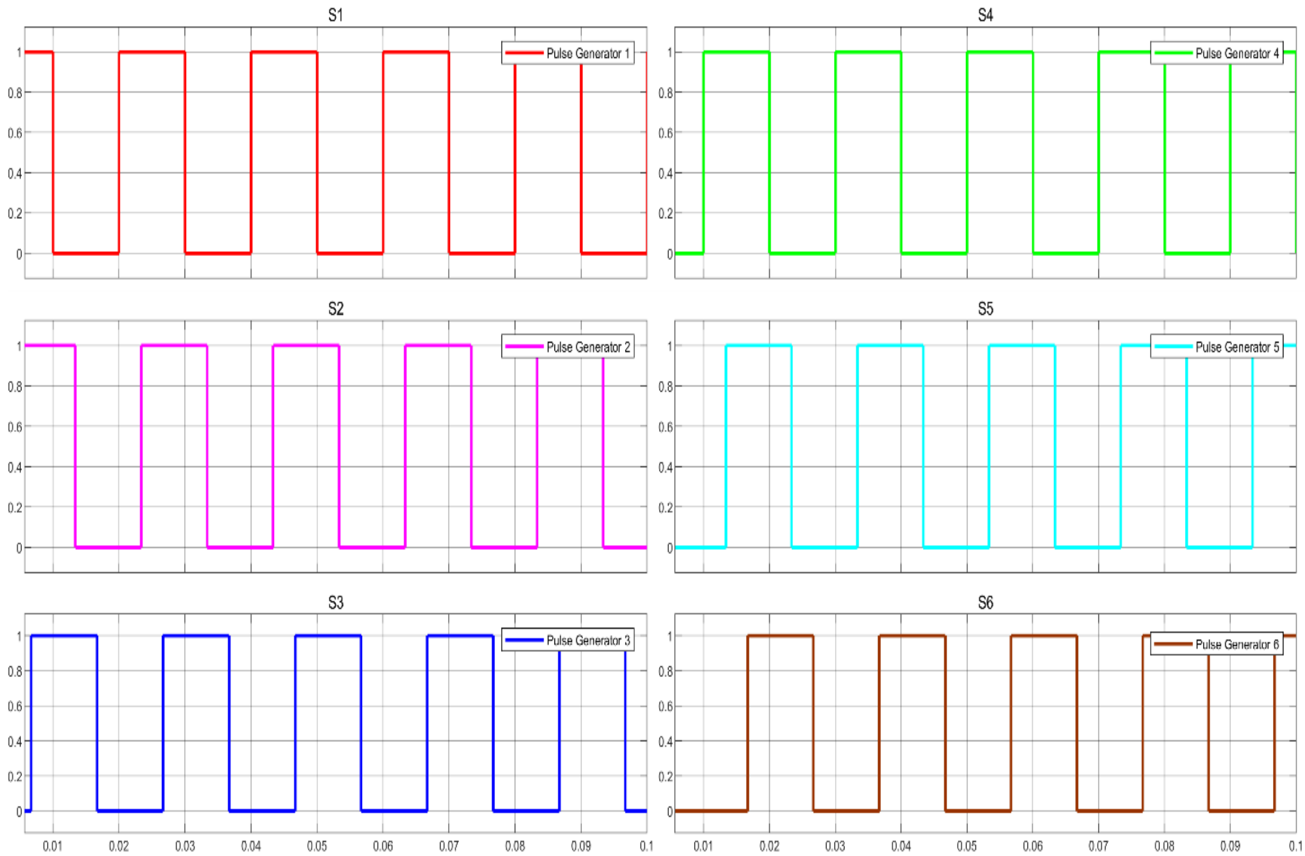

Fig. 6 *The gate pulse of Si, SiC and GaN MOSFET based inverter*

Fig. 7 presents the phase voltage of the inverter using Si, SiC, and GaN MOSFETs, showing the variation of phase voltage over time. The graph demonstrates that the peak phase voltage is approximately 200 volts for all three types of MOSFET.

Fig. 8 shows the comparison of the output waveform of line voltage for the Si, SiC and GaN MOSFET based inverter. The GaN-based inverter is represented by blue, while SiC MOSFET based inverter is using red line. The yellow line is the Si MOSFET based inverter. Observation from the graph shows that the voltage will drop after the inverter is switched on. GaN MOSFET based inverter has the minimum decrease in voltage, which only dropped approximately 0.15V. SiC as the wide bandgap semiconductor like GaN, its output voltage only had a slightly higher decreasement compared to GaN, which is approximately 0.20V. Lastly, Si MOSFET based inverter performs worst in the graph. It has the maximum drops from 300V to 299.512V.

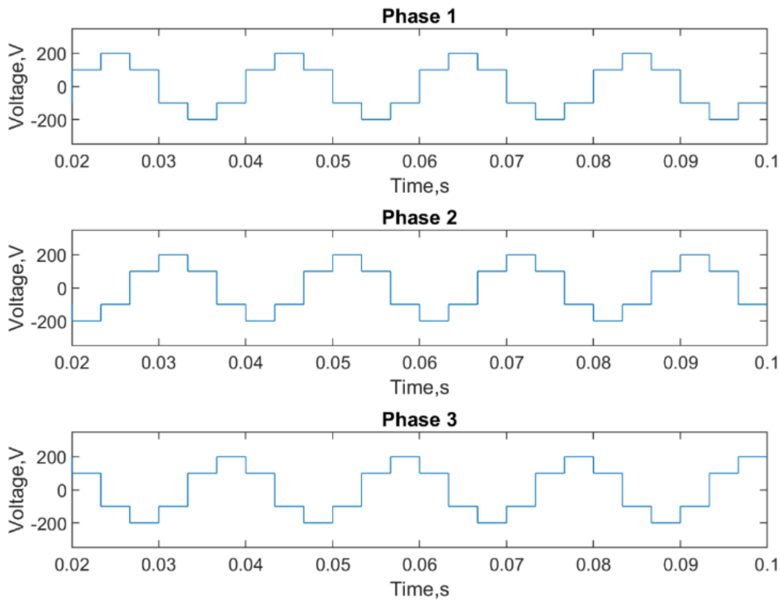

Fig. 7 *The phase voltage of Si, SiC and GaN MOSFET based inverter.*

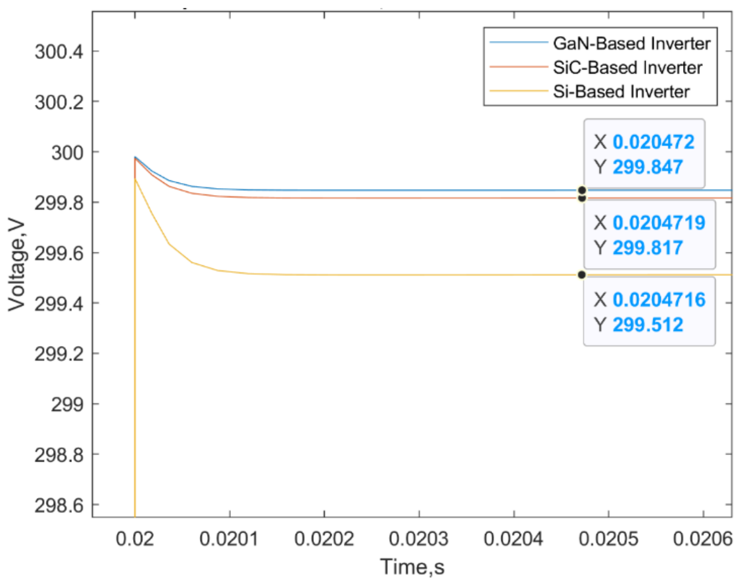

Fig. 8 *Comparison of the line voltage for the Si, SiC and GaN MOSFET. (single peak)*

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

Table 2 show the comparison of power losses including conduction loss, switching loss and total inverter loss between previous and my studies. Although there are slightly differences in the numerical values which due to the different MOSFET models used and their different properties. However, the trend alignment between the studies supports the conclusion that GaN MOSFETs perform better than SiC and Si MOSFETs in terms of conduction and switching losses. Based on the data showed that the GaN MOSFET based inverter has the lowest conduction loss among the three types of MOSFETs, with a value of 45W. At 50 Hz, Si MOSFET based inverter exhibit the highest switching loss at 0.0155 W, followed by SiC-based inverter at 0.0066W, and GaN MOSFET based inverter with the lowest at 0.0028W. Based on the calculation, Si MOSFET based inverter produces approximately 311 W of the total inverter loss, while SiC MOSFET based inverter has lower total inverter loss, approximately 302 W. However, GaN MOSFET based inverters only consume nearly 270 W for total inverter loss. Therefore, the calculation shows that GaN MOSFET based inverter are the most efficient because of the lowest inverter losses at all switching frequencies. SiC MOSFET based inverter are more efficient than Si MOSFET based inverter, as it has the highest losses and are the least efficient among the three types.

Table 2 *Loss calculations for Si, SiC and GaN-based inverter.*

Loss	Si MOSFET (W)	SiC MOSFET (W)	GaN MOSFET (W)
Conduction Loss	51.8400	50.4600	45
Switching Loss	0.0155	0.0066	0.0028
Total Inverter Loss	311.1330	302.7996	270.0167
Conduction Loss	51.8400	50.4600	45

Fig. 9 shows the relationship of total inverter losses with switching frequency from 50 Hz to 200 Hz for Si, SiC and GaN MOSFET based inverter. In terms of Si MOSFET based inverter represented by the blue line, the total inverter loss is at 311.133W at 50 Hz and increases to 311.412W at 200 Hz. This gradual increase shows that the losses are not very sensitive to the frequency, and it rises steadily. SiC MOSFET based inverter, which is the red line have a total inverter loss that starts from 302.800W at 50 Hz and it starts increases to 302.918 W at 200Hz. The losses of SiC MOSFETs are generally lower than of Si MOSFET based inverter, which identified it has higher efficiency. GaN MOSFET based inverter is represented by the yellow line and it have the least total inverter losses, which are at 270.017 W at 50 Hz and increasing up to 270.067 W at 200 Hz. This shows that GaN MOSFET based inverter are the best among others to provide the most efficiency.

Regarding to the effect of frequency, the total inverter losses of all three types of inverters increase only slightly as the switching frequency rises. The slope of loss is also very low, which means that the performance is consistent throughout the frequency range. As a result, the wide bandgap semiconductor, SiC and GaN MOSFET based inverters have higher power efficiency in compared to traditional Si-based inverter and especially in high frequency switching condition.

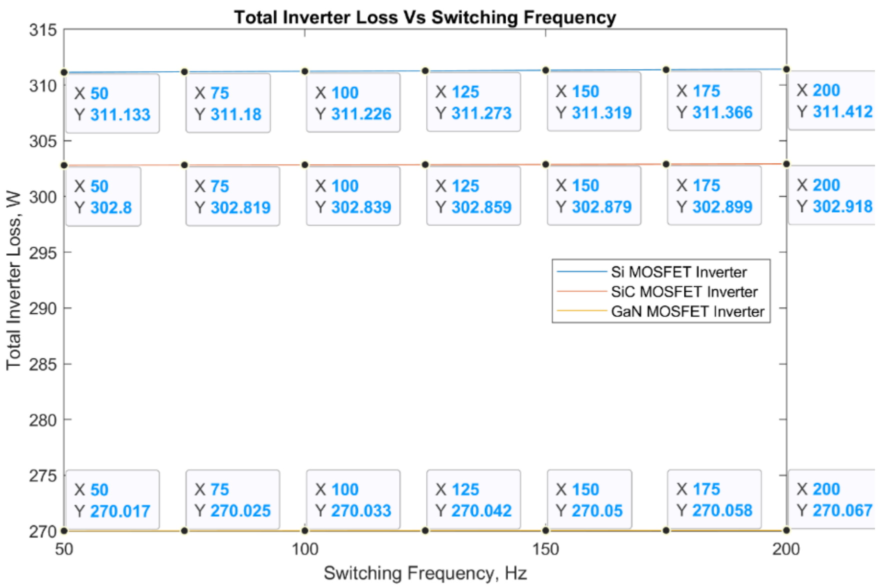

Fig. 9 *Comparison The relationship of total inverter losses with switching frequency*

Based on the output characteristics of Si, SiC, and GaN MOSFET, drain current of GaN MOSFET is much higher at various gate voltages compared to the others, which show GaN MOSFET has the ability to handle currents better at higher gate voltage compared to other materials. Meanwhile, for the transfer characteristics, GaN MOSFET offer a current of 0.0039A at a lower gate-source voltage of 1.74V, however SiC and Si MOSFET have higher gate-source voltage of 2.34V and 3.54V, respectively. This explains GaN MOSFET has a lower turn-on voltage and better efficiency than others because of its higher electron mobility and lower internal resistance.

In addition, the conduction loss of GaN MOSFET based inverter is the lowest with 45W, while SiC MOSFET based inverters are 50.4600W and 51.8400W for Si MOSFET based inverters. The switching losses of GaN MOSFET based inverter are showed lowest therefore making it the most efficient in high frequency among three types. Finally, GaN MOSFET in inverter applications are found to have the lowest total inverter loss over a frequency range of 50Hz to 200Hz. The efficiency advantage at high frequencies supports the use of GaN materials for high switching frequency applications.

4. Conclusion

In this research had been carried out comparison of Silicon (Si), Silicon Carbide (SiC), and Gallium Nitride (GaN) MOSFETs for EV charging applications by using the MATLAB and Simulink for modelling. Based on the result that showed that GaN MOSFETs were superior against other MOSFETs, with the highest drain current density, least turn-on and turn-off switching losses and the least input and output capacitance values. In other word, GaN MOSFETs as the most efficient semiconductor device for high frequency switching and high-power density applications. SiC MOSFETs also had a higher efficiency compared to Si MOSFETs especially in high voltage applications because of their lower on-state resistance and and highly electron mobility despite being slightly lower than GaN MOSFETs. Even though MOSFETs are in common use, they presented the highest conduction and switching losses and need higher gate-source voltage to deliver similar drain currents, thus having lower efficiency and being less suitable for high-frequency operation.

In the comparation of conduction and switching losses of the inverters, GaN MOSFET based inverter showed the lowest losses at all the switching frequencies, hence proved to be efficient in high-speed switching applications. SiC MOSFET based inverters had moderate losses. On the other hand, Si MOSFET based inverters had the highest losses, which supports the development of new technologies of wide-band gap semiconductor such as SiC and GaN to improve EV charging.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***data collection, prototype development and draft manuscript preparation***: *Lim Kee Han;* ***data and draft manuscript verification:*** *Muhammad Anas Razali. All authors reviewed the results and approved the final version of the manuscript.*

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