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The Performance Comparison of the SiC and Si Mosfets Used in the 3-Phase Brushless DC Motor Drives for Electric Vehicles

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Abstract

This study was carried out to compare the Silicon (Si) and Silicon Carbide (SiC) MOSFETs in the market used on motor driver circuits. A motor driver circuit is designed to run the Brushless Digital Current motors. Thanks to the semiconductors used in the driver circuit, the motor receives current as desired. While performing this task, the MOSFETs get hot and lose power. This situation changes according to the material structure used inside the MOSFETs. Hence, it is planned to compare Si MOSFETs that have been in the market for a long time and SiC MOSFETs that have been used recently under different loads and different temperatures circumstances. Si and SiC MOSFETs are placed in the motor driver circuit, which has the same structure in the simulation environment. The operation of the motor under no load and on different mechanical loads has been analysed. In these cases, the response of the MOSFETs to temperature changes was also analysed by changing the cooling temperature. As a result of the study, SiC MOSFETs were less heated and less power loss was observed than Si MOSFETs. It has been observed that when the mechanical load is high, the switching speed of Si MOSFETs decreases despite the speed of SiC MOSFETs is not affected. As a result of this study, it has been observed that SiC MOSFETs used in the motor driver circuit work more efficiently than Si MOSFETs for electric vehicles.

Keywords : Electric vehicles, 3-Phase Motor drive, Brushless Direct Current Motor (BLDC), MOSFET, Silicon Carbide (SiC) MOSFET.

Research Article

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1. Introduction

Electrical energy is the most needed form of energy in the world. The most important reason for this is that the devices around us use electrical energy. Devices that want to use this energy need different levels of energy. For this reason, power electronics materials are needed to energize the devices as desired. These materials change the energy level to keep the devices working as desired. In this case of change, while trying to bring the working materials to the desired level, efficiency loss occurs for different reasons. This loss of efficiency varies with variables such as the shape of the circuit, the operating environment of the circuit, and the nature of the materials in the circuit. Therefore, studies are carried out to reduce the efficiency loss of the circuit used to feed the electrical energy-operated devices. In order for this loss to be at an acceptable level, different circuit combinations, working in different situations, and most importantly, the materials used in the circuit are tested with different types of materials.

SiC Mosfet, produced with a new material type, has been the subject of these studies as well. Since these mosfets are brand new, some of the studies on them are on how the material performs. The effect of oxidation on Vgp due to the short gate legs of SiC Mosfets is unknown. U.Karki has analyzed SiC Mosfets and has made graphs about SiC Mosfets for this case.[1] Electromagnetic Interference (EMI) emitted by power semiconductors during operation is important. This information is known for a material like Si Mosfet that has been on the market for a long time while it is unknown about how much SiC Mosfets will emit. Thanks to this study, SiC Mosfet EMI emission is almost non-existent at low frequency values. It has been observed that SiC Mosfet emits EMI at high frequencies, but it is less than Si Mosfet .[2] There are studies on how the mosfets will react in case of a short circuit. In this study, planar and trench type SiC Mosfet were compared and it was observed that planar type SiC mosfet was more durable than trench type SiC Mosfet. [3] L.Fursin et. Al. has studied the durability of SiC Mosfets with 1200V and 3300V values. As a result of the study, it has shown findings about the reliability of mosfets that are operated for a long time. [4] In order to observe the changes that will occur when the gate resistance is different, C.Gu made a study on the operation times of SiC Mosfet. [5]

The high switching speed of power semiconductors is very important. Estimating the losses on the switching speed of the SiC Mosfet, which has a high switching speed compared to other Mosfet structures, is very important for efficiency. D.Zhang et. al. work was on this aspect. He worked to observe the losses in the high speed switching process of the SiC Mosfet used in the Half Bridge circuit. Thanks to this study, the predictability of SiC Mosfet losses has been proven. [6] H.Sayeed et. al. on the other hand, compared the SiC Mosfet used on the bidirectional switching circuit built on the PCB, in the experimental and simulation environment, and Sayeed observed that the switching performance was compatible. [7] In order to observe the advantages in switching losses, it is very important to compare the materials available in the market. W.Zhang et. al. analyzed the motor driver circuits built with SiC Mosfet and Si Mosfet separately and showed that the SiC Mosfet driver design can reduce switching losses. [8] L.Pingfei et. al. tested the driver losses of the circuits built with SiC and Si Mosfets and observed that SiC Mosfets switched faster than Si Mosfets and thus had less switching losses. [9] . S.Sabri conducted a study showing the advantages of a new generation 6.5 kV SiC Mosfet over 6.5 kV Si IGBT. In this study, he also gave information about switching losses.[10] X.Li et. al. conducted tests on the efficiency, switching performance and temperatures of SiC, Si CoolMos and Si Mosfets at the same output power and ambient temperature, and as a result of these tests, it was observed that the switching time of the SiC Mosfet was the shortest and the energy loss was the least. [11] In his study, J. Qi et. al. investigated the switching performance of 4H-SiC mosfets against Si IGBT. As a result of the studies carried out in the specified temperature range, smaller open resistance and lower switching losses were observed. [12]

The interaction of power semiconductors with temperature is substantial. For this reason, the efficiency of the devices decreases as the temperature increases. Its performance at high temperatures is very important for system efficiency. M.Mudholkar et. al. reviewed the new 1200V 20A SiC Mosfet model in the market, examined the performance between the technical temperature values and compared it with the values in the data sheet. This comparison result revealed that the material matched with the data sheet values. [13] Y.Kobayashi et. al. studied on the temperature performance and gave information about the advantages of SiC Mosfet at high temperatures. [14] Tests were carried out on high temperature in case of threshold voltage instability of Mosfets. [15]

Technological developments over time have contributed to the re-emergence of electric vehicles [16,17]. In this contribution, Çetin has studied the advantages of using SiC Mosfet in inverters used in electric vehicles. The result of this study proved that if it is used in electric vehicles, it is more efficient, takes up less space and can withstand higher temperatures.[18] W.Chou et. al. observed in his study that SiC Mosfet inverter can reduce losses and increase power density compared to Si IGBT inverter. [19] A.Acquaviva and T.Thiringer conducted a study to observe the benefits of reverse conduction in an inverter circuit with SiC Mosfet structure designed for use in electric cars. Experiments have examined the losses at different temperature values and it has been observed that reverse conduction is clearly beneficial for 3-phase systems.[20] H.Hu et. al. has tested SiC Mosfet and Si IGBT circuits designed for use in magnetic rail train. In this test, it has been observed that the switching speed of the SiC Mosfet is higher and the losses are less than Si IGBT. [21]

In the literature, there are many studies using power electronic elements consisting of different materials and structures. However, in these studies, it is very rare to compare the systems according to different structural materials and different working environments. In the literature, it was observed that existing studies were made with different types of elements. For this reason, it has not been observed how the newly discovered materials provide advantages over the same type of materials available in the market. Hence, it is planned to compare materials of the same type but with different structures. In this study, a motor driver circuit is designed for the drive system of an electric vehicle. In this driver circuit, the performances of SiC and conventional Si MOSFETs were investigated. For this comparison, both MOSFET structures were tested for different conditions, temperature and loss graphs were examined as a result of the tests. For the simulation, the features of the MOSFET samples that are already available in the market were used. In the analysis, the PSIM program, which is widely used in the literature and proven to be accurate, was used and the 3-phase motor driver model created was explained in detail.

2. Si and SiC MOSFET structures

MOSFETs are commonly used materials in energizing. It is indispensable especially for devices that require high switching speed. Silicon MOSFETs in terms of material structure have been on the market for a long time. As a result of studies on new material structures, a new structured MOSFET has emerged and this new structured is SiC MOSFET. These MOSFETs are more advantageous than Si MOSFETs. In terms of band gap energy, Si MOSFETs have a range of 250-300 ºC, while this range is 600-800 ºC in SiC MOSFETs. In this way, they work more safely at high temperatures. Thanks to this band gap, it is more suitable for high frequency switching. This is because SiC MOSFETs have lower capacitance values. There are 3 capacitances in the structure of MOSFETs: Input capacitance (Ciss), Output capacitance (Coss) and Reverse transfer capacitance (Crss). These capacitance values affect the switching speeds less due to their low values. It is the internal resistance of the MOSFET that determines the energy loss during switching. Since internal resistance is less in SiC

MOSFETs, energy loss is less than Si MOSFETs. In terms of material structure, the thermal conductivity of SiC MOSFETs is better than Si MOSFETs. In this way, it conducts heat well and creates fewer heating problems at high powers. As a result of these values, circuits with better power efficiency and less loss are created, resulting in energy saving circuits.

The most important criteria in the selection of these MOSFETs is the same continuous output current values. It will be more convenient to compare the MOSFETs with the same continuous output current values. Another condition is that these MOSFETs are already using in the market. For this reason, it is planned that the data of the MOSFETs will be transferred to the simulation environment more accurately and the obtained data will be closer to the real-world data. In this article, two different types of MOSFETs available in the market to be used in the motor driver circuit designed to observe these advantages are determined. These MOSFETs are IRFP460 (Si MOSFET) and SCT20N120 (SiC MOSFET). Table 1 was created as a result of examining the data sheets of the mosfets according to the parameters we mentioned above.

3. Motor drive design

Engine selection is important in electric vehicles. For these motors, high torque at the first start and low power consumption criteria are sought at high speeds. As a result of the studies, BLDC motors with higher efficiency compared to other motors that can operate at high torque are seen. [22,23] For this reason, it has been seen that BLDC motor is suitable for electric vehicle. BLDC Motors consist of two types of structures, with sensors and sensorless. Sensorless BLDC motors do not have Hall Effect sensors in their internal structure and the position of the rotor is determined by the reverse EMF control. Therefore, they are more difficult to control. It is easier to find the position of the rotor with Hall Effect sensors in BLDC motor structures with sensors. Due to these structures, there are more than one control method. [24] The driver circuit is created in the PSIM program, as in Fig. 1. The circuit filtering consists of a three-phase inverter, a BLDC motor with sensors, and a DC power supply. Motor parameters are given in Table 2.

Table 1. Structural values of determined MOSFETs

	IRFP460	*SCT20N120*	*Unit*
Continuous Output Current	20	20	A(25^{O}C)
Instantaneous Peak Current	80	45	A(25^{O}C)
Drain-Source Max. Voltage	500	1200	V
MOSFET Internal Resistance	0.24	0.189	Ω
Input Capacitance (C_{iss})	3000	650	pF
Output Capacitance (C_{oss})	480	65	pF
Feedback Capacitance(C_{rss})	270	14	pF

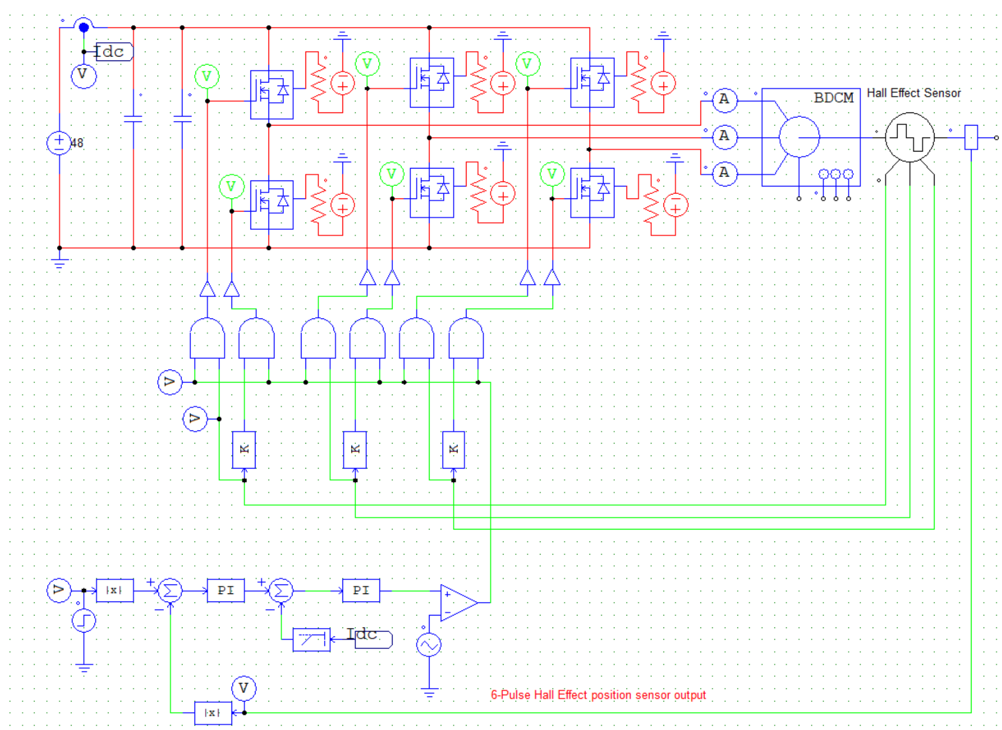

Fig. 1. PSIM Simulation Circuit.

Table 2. BLDC motor features used in PSIM simulation

Parameter	Value	Unit
Number of Phase	3	
Number of Poles	4	
No-Load speed	3000	rpm
No-Load Current	3.88	A
Voltage	48	V

The temperature of the voltage source cooler, which is shown in red on the extra legs of the MOSFETs in this circuit, is determined. In this way, it can be observed how the system will react at what temperature. The resistance in this circuit is the thermal resistance of the cooler. The position information of the motor is obtained with 3 Hall Effect sensors in the structure of the BLDC motor with sensors. With the position information coming from these sensors, the phases are energized differently, and the motor starts to rotate. In order for the motor to turn, the inverter must be controlled. The feedback of the Hall Effect sensors inside the motor is processed, thus energizing the phases required for the motor to rotate. In Table 3, the MOSFET switching information of the motor driver is given with the feedback from the Hall Effects.

Table 3. Hall Effect truth table

	Hall Effect Sensors			A	A	B	B	C	C
	A	B	C	High	Low	High	Low	High	Low
1	1	0	1	0	0	1	0	0	1
2	1	0	0	0	1	1	0	0	0
3	1	1	0	0	1	0	0	1	0
4	0	1	0	0	0	0	1	1	0
5	0	1	1	1	0	0	1	0	0
6	0	0	1	1	0	0	0	0	1

BLDC motor has 6-stage control algorithm. The MOSFETs in the inverter are switched on the signals coming from Hall Effects. These switching are made sequentially as in Table 3, so that the motor makes one full revolution. For example, when only B logic1 feedback is received from Hall Effect sensors in stage 4, the high MOSFET in phase C is switched while the low MOSFET in phase B is switched to complete the circuit. Then, for the motor to rotate in the specified direction, it returns to the beginning after stages 5 and 6 have occurred, and so on. This signal algorithm has been applied in the simulation circuit in Fig. 1 and the signal that comes out of the green voltage probes on the gate leg of the MOSFETs in the simulation circuit is shown in the Fig. 2.

In Fig. 2, (X) represents AH-AL signal, (Y) represents BH-BL signal and (Z) represents CH-CL signal. When the measured signals are compared with the table in Table 3, the ranking matches the table. The signal started from the 4th stage from the point where it could be measured, after the 5th and 6th stages were observed, it returned to the 1st stage and continued according to the order in the table. In this way, it is ensured that the engine takes a full revolution with stability.

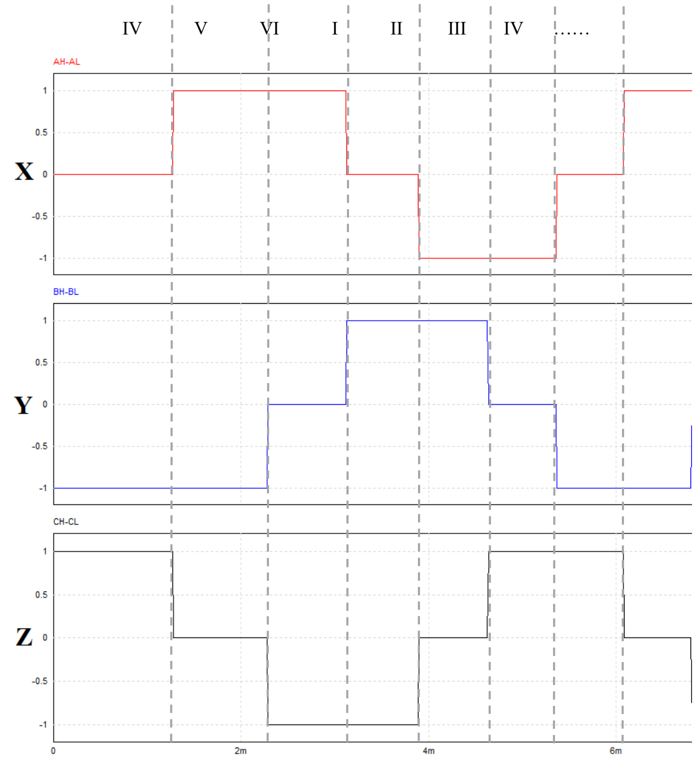

Fig. 2. Simulation of MOSFETS switching signals for inverter

4. Simulation

Before starting the simulations on the inverter, the operation of the MOSFETs on the simple circuit in Fig. 3 was examined without examining the temperature values and losses in order to work in the inverter.

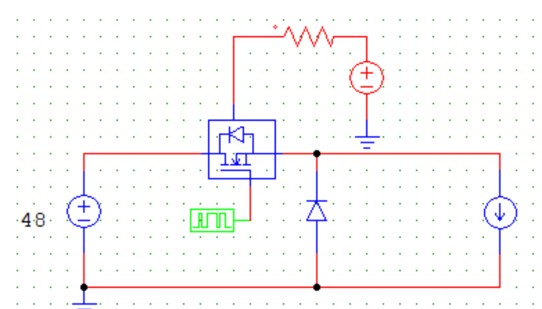

Fig. 3. Simulation Test Circuit

In this created circuit, a preliminary information has been gained for the temperature values and losses according to the values of the MOSFET at different frequency values and at different loads. The circuit on the extra leg of the MOSFETs that determines the ambient temperature has been determined as 40ºC, which is the Junction-to-Ambient values of the MOSFETs. MOSFETs were driven with a green signal generator at frequency values of 1 kHz, 2.5 kHz, 10 kHz, 25 kHz and 50 kHz and current values of 2 A, 5 A, 10 A, 15 A and 18 A. The direct voltage source of the circuit is 48 volts. The values taken for the simulation IRFP460 are shown in Fig. 4 and 6, and for the SCT20N120 in Fig. 5 and 7.

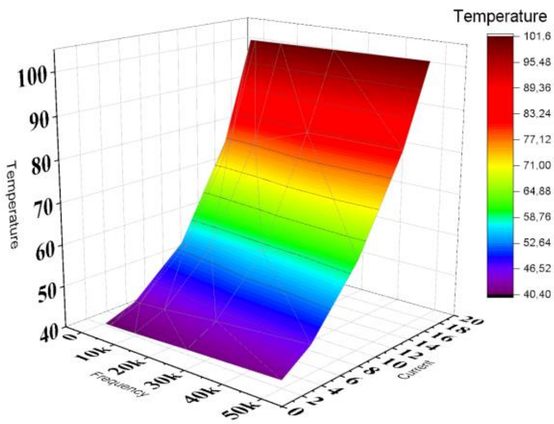

Fig. 4. Frequency-current-temperature graph for IRFP460

Considering the simulation results, the IRFP460 temperature values reach 100ºC for each frequency value at high currents, while the losses are based on 80 Watts. However, when looking at the frequency values for the SCT20N120, the maximum temperature value was 83 degrees for 50 kHz, while different temperatures were measured for each frequency value. Considering the losses, 51 watts was measured for 50 kHz. When the graphics are examined, more heating and loss values are observed for IRFP460 when frequency and current values increase, while 20% less heat and 35% less loss are observed for SCT20N120. By examining these values, the frequency value selected for the motor driver to be studied on Fig. 4 is 10 kHz. The determined frequency and the values obtained from the simulation are shown in Table 4.

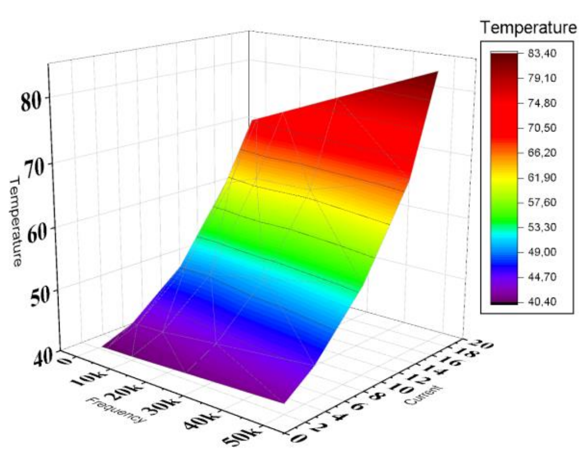

Fig. 5. Frequency-Current-Temperature graph for SCT20N120

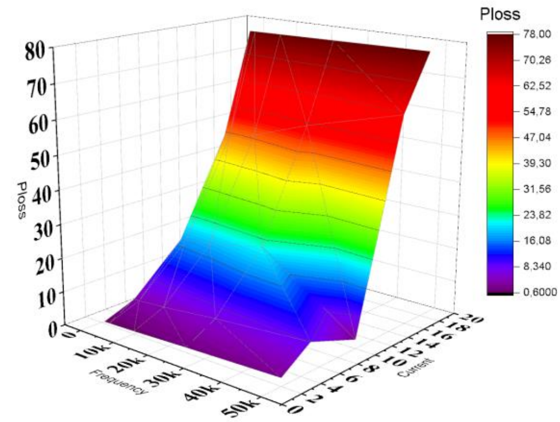

Fig. 6. Frequency-Current-Power loss graph for IRFP460

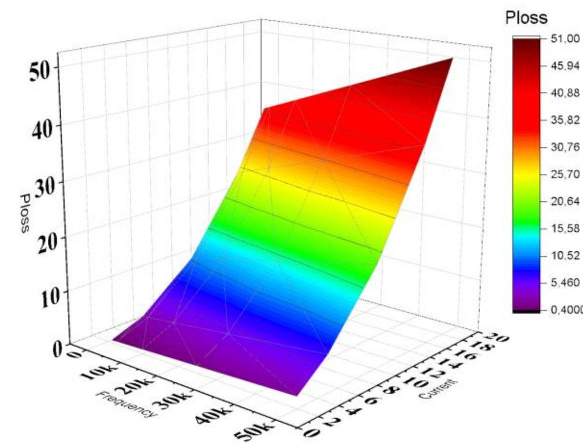

Fig. 7. Frequency-Current-Power Loss graph for SCT20N120

Table 4. Simulation results obtained at 10 kHz

	Current(A)	Temperature(ºC)	Ploss(W)
IRFP460	2	40.67	0.85
SCT20N120	2	40.61	0.82
IRFP460	5	43.60	4.55
SCT20N120	5	42.63	3.51
IRFP460	10	54.67	18.58
SCT20N120	10	49.32	12.21
IRFP460	15	77.95	48.04
SCT20N120	15	62.92	26.96
IRFP460	18	100.88	77.06
SCT20N120	18	73.02	38.85

Different results were obtained for the developed motor driver according to the cooling temperatures. First, the system was operated at a cooling temperature of 25ºC. Table 5 was created with the values obtained as a result of this simulation.

Brushless DC motor in the circuit has table 1 values. The developed motor driver was analysed under four different conditions, no-load and under different mechanical loads. In these cases, three different values as 25ºC 40ºC and 85ºC were examined as cooling temperatures. Although the developed motor driver was operated at different temperatures, no changes in current were observed. This situation is shown in Table 5,6,7.

Table 5. Simulation with Cooling Temperature 25ºC

	Current(A)	Temperature(ºC)	Ploss(W)
IRFP460	3.88	26.78	3.24
SCT20N120	3.88	27.08	2.80
IRFP460	7.84	33.57	15.59
SCT20N120	7.84	33.05	10.73
IRFP460	11.65	47.27	40.50
SCT20N120	11.65	45.57	27.43
IRFP460	14.94	71.20	84
SCT20N120	14.94	62.77	50.36

In the simulation, the temperature and loss values were observed to be close to each other according to the no-load state of the motor at the beginning, but it was observed that the temperature and loss difference between Si and SiC MOSFETs increased as the mechanical load was connected to the motor and this value continued to increase. In the circuit with the highest mechanical load, the current drawn by the motor is the same for both MOSFETs, while the temperature difference is 9ºC and the loss is close to 34 Watts. The graph showing this situation is shown in Fig. 8.

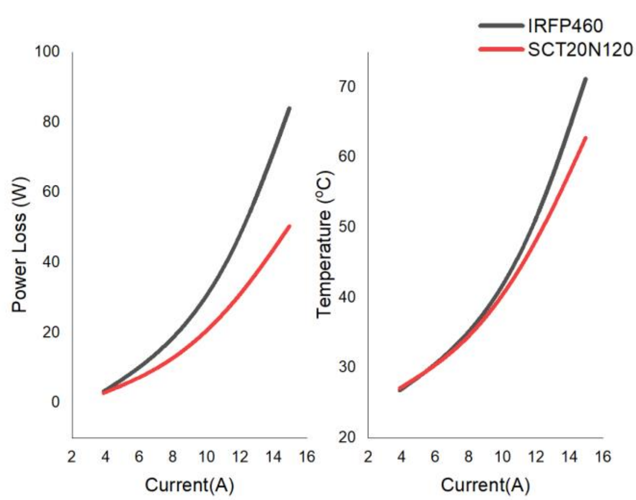

Fig. 8. MOSFET states at 25ºC cooling temperature

In the graph, the MOSFETs are arranged according to the current drawn by the motor. According to this current, the difference between the temperature and power losses of the MOSFETs was observed and this observation is clearly seen in the graph.

In another simulation, the cooling temperature was determined as 40 ºC. Another reason for choosing this value is that the Thermal resistance junction-ambient (Rthj-amb) values of the MOSFETs are the same. The values obtained from this simulation are observed in Table 6.

In the simulation with the cooling system temperature of 40ºC for the developed motor driver, it has been observed that the values are close in the no-load state of the motor. As the mechanical load connected to the motor starts to increase, the temperature and loss difference between them is greater than the simulation in Table 5. When examined according to the maximum mechanical load, the difference in power loss increased gradually when the temperature increased. The graph in Fig. 9 was observed according to these values.

Table 6. Simulation with Cooling Temperature 40ºC

	Current(A)	Temperature(ºC)	Ploss(W)
IRFP460	3.88	42.08	3.78
SCT20N120	3.88	42.06	2.75
IRFP460	7.84	48.43	15.33
SCT20N120	7.84	47.70	10.27
IRFP460	11.65	65.36	46.10
SCT20N120	11.65	59.86	26.48
IRFP460	14.94	91.22	93.13
SCT20N120	14.94	78.26	51.02

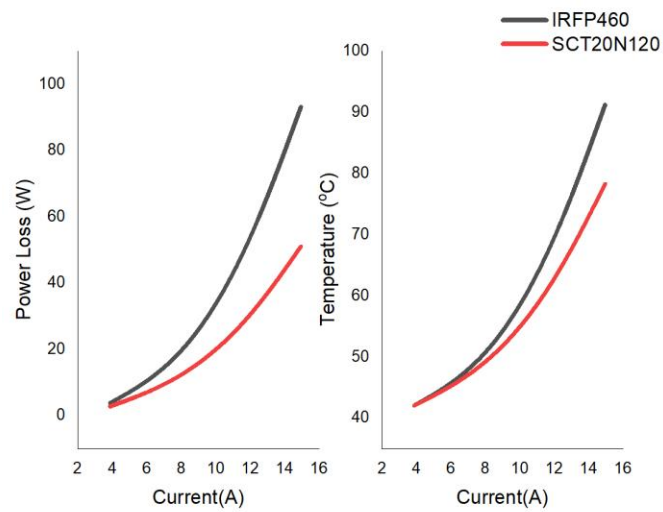

Fig. 9. MOSFET states at 40ºC cooling temperature

In the simulation at 40ºC, the temperature value differences were observed approximately the same as in the simulation at 25ºC this situation is not the same for loss. According to the reported values, the difference between the power losses gradually increased. The most important reason for this is that more power loss is observed in the IRFP460 MOSFET.

In the last simulation, it is desired to observe the loss and temperature change of the MOSFETs at high temperature. For this reason, the cooling temperature was determined as 85ºC and the values in Table 7 of the system results were revealed.

Table 7. Simulation with Cooling Temperature 85ºC

	Current(A)	Temperature(ºC)	Ploss(W)
IRFP460	3.88	87.88	5.23
SCT20N120	3.88	87.12	2.83
IRFP460	7.84	96.88	21.60
SCT20N120	7.84	93.53	11.37
IRFP460	11.65	118.55	61
SCT20N120	11.65	105.23	26.98
IRFP460	14.94	150.76	119.56
SCT20N120	14.94	124.54	52.72

A simulation with a cooling temperature of 85ºC was made to examine the high-temperature operating state of the MOSFETs.

Despite the no-load state of the motor, the power loss difference between the IRFP460 and the SCT20N120 is greater than the no-load state conditions at other temperatures. If this value is at the highest mechanical load, power loss conditions SCT20N120 MOSFET loses half as much power as IRFP460 MOSFET. It was prepared according to the value in Table 7 in Fig. 10.

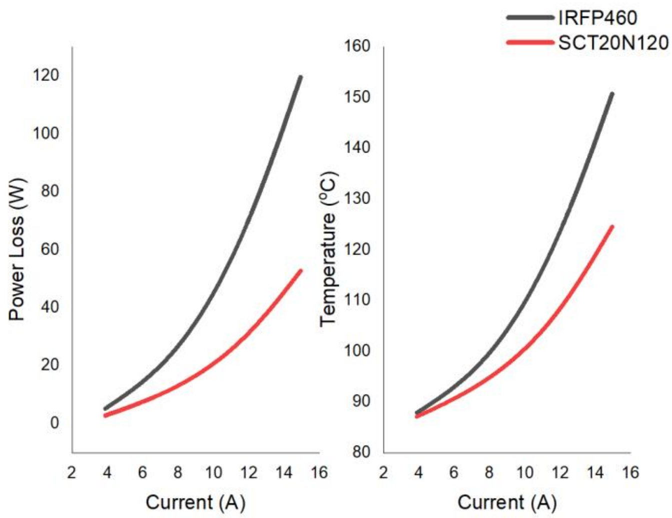

Fig. 10. MOSFET states at 85ºC cooling temperature

When the graph of the MOSFETs operating at high temperatures is examined, it is observed that the temperature difference is greater. The loss in IRFP460 at high temperature is quite high. This leads to lower yields and faster deterioration. On the other hand, SCT20N120 power losses at different temperatures are approximately the same. After the simulations, it was requested to evaluate the materials among themselves. Fig. 11 for IRFP460 and Fig. 12 for SCT20N120 was created.

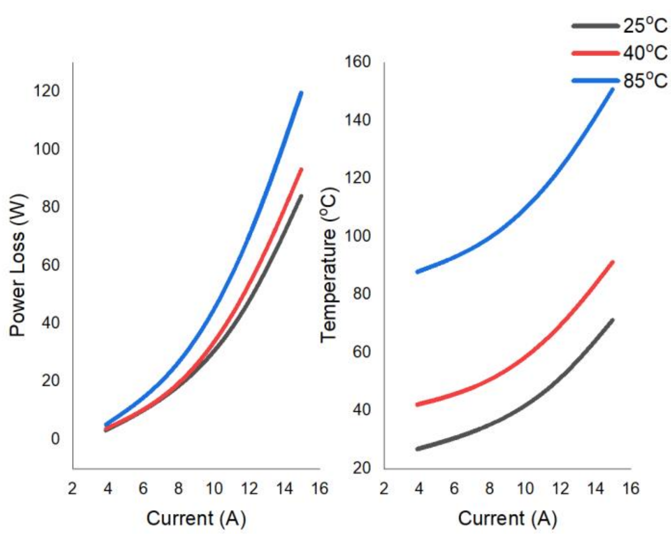

Fig. 11. IRFP460 values according to different cooling temperatures

This chart is about examining the IRFP460 MOSFET operating at different temperatures. When analysed in terms of loss, losses are approximately the same in case of MOSFET no-load state operation. Due to the mechanical load on the motor, the MOSFET operating in a hot environment has lost more power. This reduced the efficiency of the system. While the systems operated at 25 and 40ºC have approximately the same power loss when the mechanical load is low, this difference has gradually increased with the increase in the load.

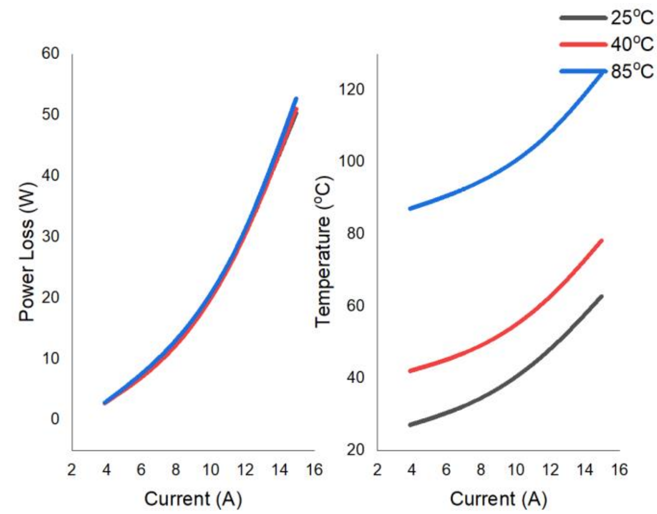

Fig. 12. SCT20N120 values according to different operating temperatures

In this graph, the loss and temperature values of the SCT20N120 MOSFET operated at different cooling temperatures are observed. When the graph is examined, although it has different temperature values, approximately the same values are observed in terms of MOSFET power loss. This shows that the MOSFET maintains its efficiency value more easily.

A situation that is examined as a result of the simulation is the switching speeds of the MOSFETs. The results related to this are shown in Fig. 13.

The graph of the current flowing through the MOSFET on a phase is given according to the motor no-load state. In the given graph the red signal is the IRFP460 the blue signal is the signal of the SCT20N120 graph. Temperature values are 25 40 and 85ºC from top to bottom. When the engine is no-load state, the difference between the switching speeds is small, but it starts to increase as the temperature increases. This difference became wider as the mechanical load increased. The condition of the motor operates at the highest load is shown in Fig. 14.

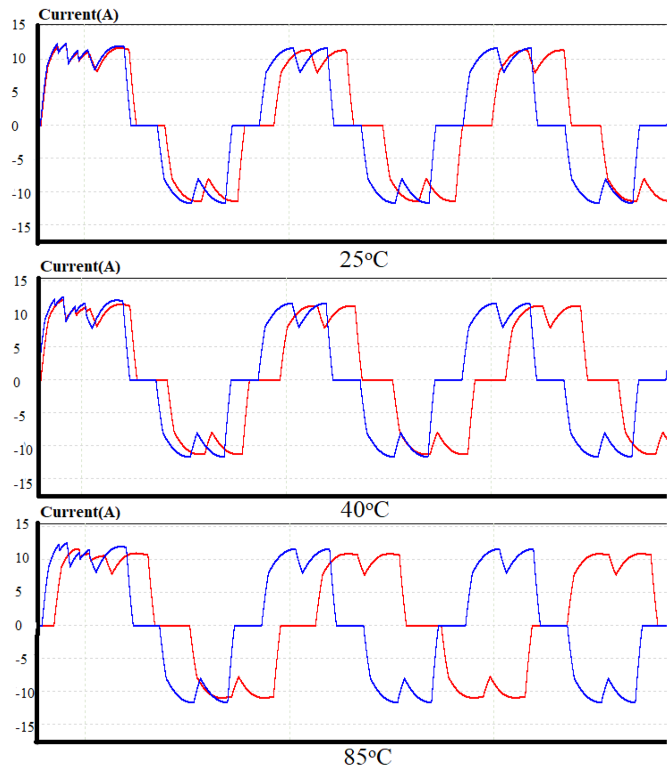

Fig. 13. Graph of current according to the no-load state of the motor

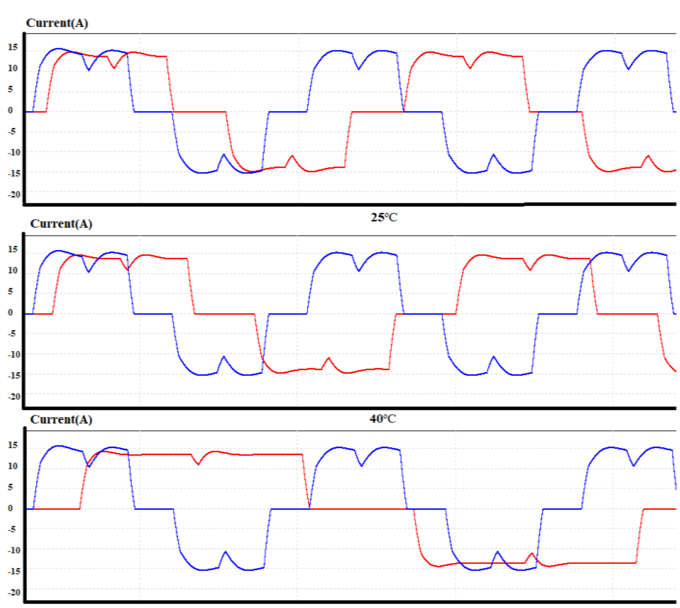

Fig 14. Graph of the motor running at the highest load

In the graph, the switching speed state is more pronounced than the no-load state. Slippage can be observed more easily even in low temperature operating conditions. In this case, it has been observed that the SCT20N120 operates at the same speed despite the temperature change, while the switching of the temperature changes is slower for the IRFP460.

Signals with single phase are given in Fig. 14. In this signal, the motor is in the state where it draws the most current in the simulation. When the resulting signals were examined, no change was observed in the switching speed, although the temperatures of the SCT20N120 changed. This does not apply to the IRFP460. The MOSFET, which is observed to change the switching speed even in the idling state of the motor, more shifts were observed in the case of the current drawn by the motor the most.

5. Conclusion

MOSFETs are widely used materials for energizing in power electronics systems. These materials are ideal in high switching applications. In terms of material structure, Silicon MOSFETs have been on the market for a long time, while novel-structured Silicon Carbide MOSFETs exist more recently. SiC MOSFETs have more advantageous characteristics as given in the literature. These MOSFETs have a larger band gap energy and better thermal conductivity than conventional Si MOSFETs. In addition, the lower internal structural capacitance and switching resistance values indicate that the switching losses will be less.

In this paper, a comparison of Si and SiC MOSFETs are used to designed motor driver separately. Two motor driver circuits are designed in the PSIM simulation program to accomplish the comparison. The motor drivers have been investigated for different load values and different temperatures on the same motor. As a result of the simulation, while the Si and SiC MOSFETs are almost not different in the no-load state of the engine, differences are observed according to the mechanical load and temperature values. Also, Si MOSFETs heat up to 22% more than the SiC MOSFETs under same circumstances. Another interesting observation is the switching speed of the Si MOSFETs decrease, while the switching speed of the SiC MOSFETs was not affected during the high current operation. Besides, Si MOSFETs power loss is more than double in comparison to the SiC MOSFETs due to more heating and slower switching speed. In conclusion, SiC MOSFETs work significantly more efficient than Si MOSFETs in the motor driver circuit under the same circumstances in the simulation

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Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Erkan Sevim: Conceptualization, Validation, Formal analysis, Investigation, Methodology

Emrah Çetin: Supervision, Conceptualization, Project administration

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