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Analysis of the Effectiveness of Silicon Carbide Usage in the Jakarta Metro Traction System Using Matlab

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ABSTRACT

Switching inverter technology for converting DC to AC using Insulated Gate Bipolar Transistors (IGBTs) has been implemented in the propulsion system of the Jakarta Metro. However, with advancements in power electronics, a newer technology—Silicon Carbide (SiC)—has emerged, offering the potential to reduce switching power losses by up to 30%. The effectiveness of this technology can be evaluated through simulations using MATLAB Simulink, enabling an assessment of its potential application in the Jakarta Metro system. By quantifying this efficiency gain, informed strategic decisions can be made regarding the adoption of SiC technology for DC to AC conversion, whether through the replacement of existing IGBT-based inverters or during the procurement of rolling stock for future phases.
The evaluation will be conducted by simulating both existing IGBT parameters and proposed SiC device parameters under current traction motor operating conditions. This simulation aims to determine the output power required to drive the traction motor while maintaining alignment with the current train configuration. A comparative analysis of efficiency between the two technologies will form the basis of this thesis, providing insights into the feasibility and benefits of transitioning to SiC-based inverters for the Jakarta Metro.

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1. INTRODUCTION

The Electric Multiple Units (EMUs) operated by Metro Jakarta are self-propelled railway vehicles that utilize electric power without the need for a separate locomotive. The propulsion system currently in use employs inverters based on Insulated Gate Bipolar Transistor (IGBT) technology to convert direct current (DC) to alternating current (AC), which is then used to drive the traction motors.

Recent advancements in power electronics have introduced Silicon Carbide (SiC) as a more efficient switching component compared to conventional IGBT technology. The integration of SiC-based inverters has the potential to significantly improve energy efficiency and reduce environmental impact. This technology can be implemented either in the current fleet of EMUs or in future units, should there be an expansion.

To evaluate the feasibility and potential benefits of adopting SiC technology, this study employs a comparative methodology. The comparison involves simulating several operational scenarios using MATLAB/Simulink, which allows for the assessment of both IGBT and SiC performance under equivalent conditions. This approach is particularly suitable given the custom nature of EMU designs, which are typically tailored to the specific requirements of operators.

Due to the limitations of direct experimentation with existing EMUs, simulation provides a practical means to estimate the effectiveness of SiC integration. The outcomes of these simulations will yield quantitative measures of energy efficiency, which will serve as critical inputs for strategic decision-making regarding the retrofitting of existing units or the procurement of new EMUs in subsequent development phases.

2. RESEARCH METHOD

The traction motor used is a squirrel cage type, supplied with three-phase voltage regulated by a VVVF (Variable Voltage Variable Frequency) inverter. The continuous voltage supplied is 1100 V, while the continuous current is 85 A. The table below presents the specifications of the traction motor used in the Jakarta Metro rolling stock.

Table 1. Traction Motor Specification[1], [2]

Category	Specification
Continuous Power Rating	126 kW
Continuous Voltage Rating	1.100 V (tegangan nominal 1.500 Vdc)
Continuous Current Rating	85 A
Continuous Frequency Rating	74 Hz
Wheel Diameter	860 mm
Pole	4
Maximum Speed	4.444 min^{-1} (100 km/jam)

The data collection in this study is conducted by simulating a three-phase inverter using MATLAB–Simulink software. The simulation is carried out in two approaches: with a static load and with a dynamic load.

IGBT is a switching component that shares similar characteristics with MOSFETs but offers higher switching speed, greater current-handling capability, and lower resistance compared to MOSFETs. The IGBT shares a similar construction with the MOSFET, with the key difference being the addition of a p+ layer at the drain region of the MOSFET structure. Like power MOSFETs, a positive voltage applied between the gate and emitter in an IGBT allows current to flow, turning the device on. When the IGBT is on, positive charge carriers are injected from the p+ layer into the n-type drift region, thereby enhancing conductivity modulation. This mechanism enables the IGBT to achieve a significantly lower on-state resistance compared to MOSFETs. The resistance of the n-type drift layer in the IGBT becomes very low due to the formation of a pn diode, created by the added p+ layer and the n-type drift region when viewed from the drain side.[3], [4]

Based on existing research, SiC offers numerous advantages, including reduced heat generation, the need for smaller cooling components, and the ability to deliver higher power output. Additionally, SiC features higher blocking voltage, lower resistance, and reduced switching losses compared to IGBT or traditional silicon (Si) devices. In terms of application, SiC can operate at higher voltage, frequency, and temperature levels, while remaining lighter and more compact, thereby improving overall system efficiency. [5]

Other studies have also shown that SiC can be used to optimize switching frequency in EMU propulsion inverters, aiming to maximize efficiency. Due to its low switching power losses, SiC enables higher switching frequencies. [6]

The following is a comparison of the characteristics between Si and several other semiconductor materials:

Table 2. Comparison of The Characteristics Between Si and Several Other Semiconductor [7], [8]

	Si	**GaAs**	**6H-SiC**	**4H-SiC**	**GaN**	**Diamond**
Bandgap E_g (eV)	1.12	1.43	3.03	3.26	3.45	5.45
Dielectric constant ε_r	11.9	13.1	9.66	10.1	9	5.5
Electric Breakdown Field E_c (kV/cm)	300	400	2,500	2,200	2,000	10,000
Electron Mobility μ_n (cm^2/V.s)	1,500	8,500	500	1,000	1,250	2,200
Hole Mobility E_p (cm^2/V.s)	600	400	101	115	850	850
Thermal Conductivity λ (W/cm.K)	1.5	0.46	4.9	4.9	1.3	22
Saturated electron drift velocity V_{sat} (×107 cm/s)	1	1	2	2	2.2	2.7

This table below shown the key points of comparation between SiC Mosfet and IGBT as simulated in PSIM.

Table 3. Comparation Between Silicon Carbide Mosfet and IGBT based Electric Vehicle Traction Inverter

Category	SiC	IGBT
Simulation Environment	PSIM	PSIM
Load Condition	Varied	Varied
Performance summary	Expected to have lower on-resistance, higher breakdown voltage, leading to potentially better efficiency and lower energy losses	Generally has higher on-resistance, leading to potentially less efficiency compared to SiC
Technology	SiC (Silicon Carbide) based, offering inherentadvantages over Si (IGBT)	Si (Silicon) based, traditional technology in EV traction inverters
Application for EVs	Analyzed for range extension and performance enhancement in EVs	Evaluated for its current role and potential improvements in EV

3. MATLAB SIMULATION AND PERFORMANCE EVALUATION

3.1. Static Load

The first simulation will evaluate conditions under a static load. The parameters used are as follows:

Table 4 – Parameter for IGBT Simulation Static Load

Parameter	Value
Voltage (DC)	1500 V
Inverter : Snubber Resistance	10000 Ohm
Inverter : Snubber Capacitance	1*10^{-6} F
Inverter : Ron	0,05 Ohm
PWM Generator : Frequency	800 Hz
LC Filter : L	3*10^{-3} H
LC Filter : C	100*10^{-6} F
RL Load	Setara dengan 126KW

The parameters listed above are implemented in the following simulation using MATLAB Simulink. This section focuses on the static load condition, where the voltage rating is assumed to be constant at 1500 VDC, and the load is equivalent to four traction motors operating at a constant power output of 504 kW. Instead of modeling the actual motors, the load is represented by an RL (resistor–inductor) circuit that is electrically equivalent to the load experienced by the inverter.

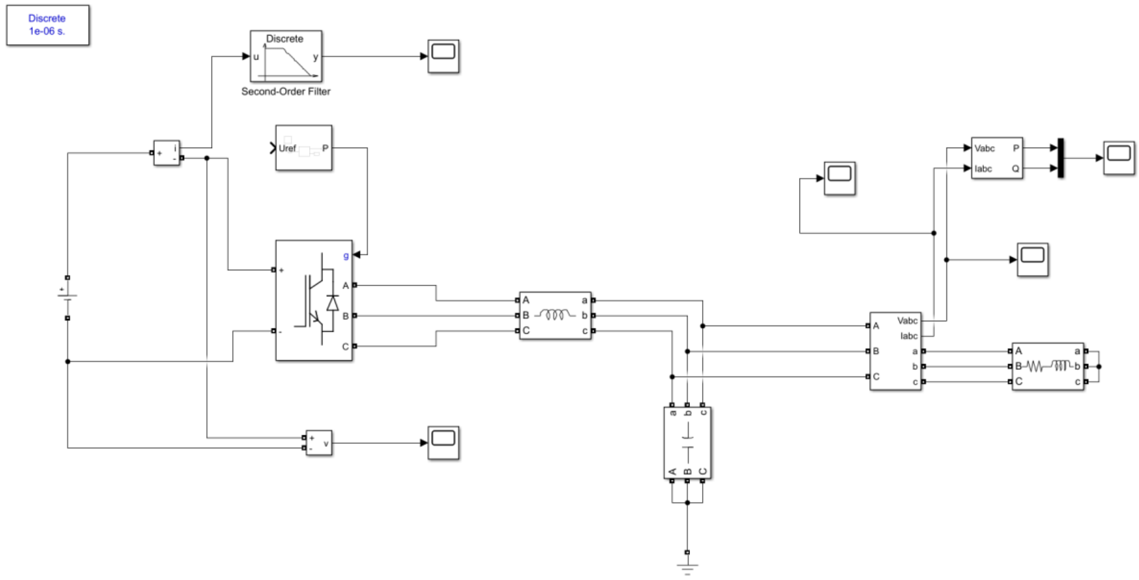

Figure 1. IGBT Static Load Model

The switching performance simulation using IGBT, as presented above, will be compared with the results of a simulation using SiC in the following section. The results of the above simulation are as follows:

Table 5 –IGBT Simulation Static Load Result

Parameter	Result
Voltage (DC)	1500 V
Current input (depending on load applied)	88,4 A
Power input	1500*87 = 132,6 KW
V peak Output	4740 V
V rms	3675 V
Current output I peak	29.6 A
Current I rms	23 A
RL Load	Equal = 126KW
Power Active	$1,26*10^5$ Watts = 126 KW
Inverter efficiency (output power / input power)	126 / 132,6 KW = 95,02 %

The simulation in this section still utilizes a static load; however, the inverter component is replaced with a SiC-based device, whereas the previous simulation used an IGBT-based inverter. The parameters used in this simulation are as follows:

Table 6 – Parameter for SiC Simulation Static Load

Parameter	Value
Voltage (DC)	1500 V

Inverter : Snubber Resistance	10000 Ohm
Inverter : Snubber Capacitance	$1*10^{-6}$ F
Inverter : Ron	0,05 Ohm
PWM Generator : Frequency	800 Hz
LC Filter : L	$3*10^{-3}$ H
LC Filter : C	$10*10^{-6}$ F
RL Load	Setara dengan 126KW

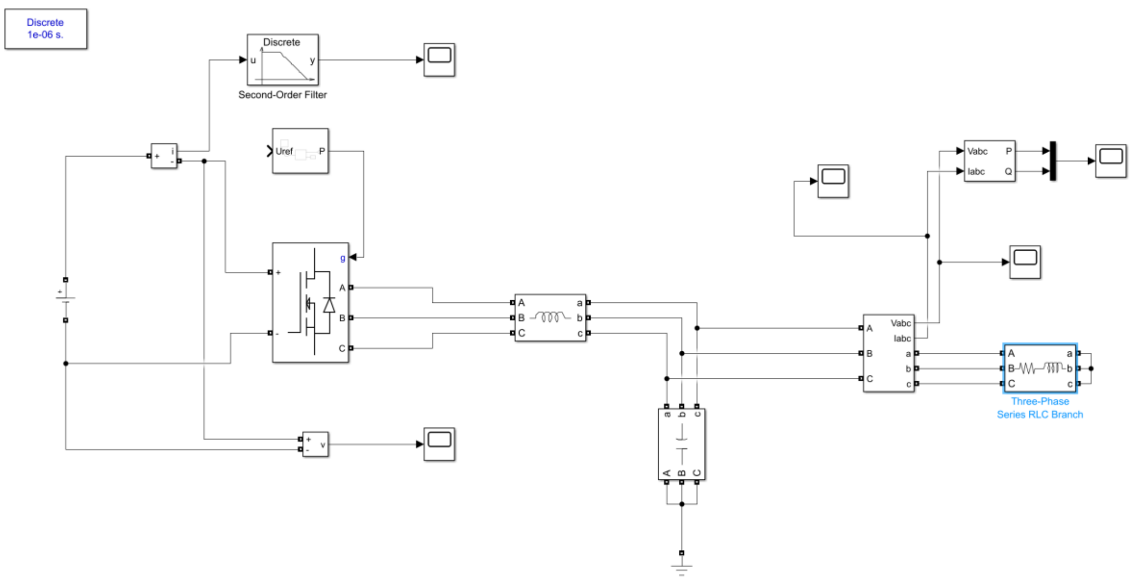

Figure 2. SiC Static Load Model

The switching performance simulation using SiC, as presented above, will be compared with the results of a simulation using SiC in the following section. The results of the above simulation are as follows:

Table 7 – SiC Simulation Static Load Result

Parameter	Result
Voltage (DC)	1500 V
Current input (depending on load applied)	87,17 A
Power input	1500*87,17 = 130,755 KW
V peak Output	4694 V
V rms	3663 V
Current output I peak	29,3 A
Current I rms	22,9 A
RL Load	Setara dengan 126KW
Power Active	$1,26*10^5$ Watts = 126KW
Inverter efficiency (output power / input power)	126 / 130,755 KW = 96,36 %

After conducting the two simulations, a comparison can be made between Simulation 1, which uses an IGBT-based inverter, and Simulation 2, which uses a SiC-based inverter. Both simulations are subjected to the same static load. The comparison of the two simulations is presented in the table below:

Table 8 – Comparation of Simulation Static Load Result

Components	**Power Output**	**Power Input**	**Input Current at DC Constant (1500VDC)**	**Inverter Efficiency**
IGBT	126 KW	132,6 KW	1500 V	95,02 %
SiC	126 KW	130,755 KW	1500 V	96,36 %

From the comparison results above, it can be observed that the output power is maintained at a constant level in order to accurately compare the input power, which serves as the basis for calculating inverter efficiency. The inverter efficiency using the IGBT device is recorded at 95.02%, while the efficiency using the SiC device is 96.36%.

3.2. Performance Evaluation of IGBT and SiC MOSFET with Traction Motor (Dynamic Load)

The second simulation will demonstrate the performance of both IGBT and SiC under dynamic load conditions. The load is modeled using the same traction motor applied in Jakarta Metro trains. The following parameters are used for the simulation of IGBT performance with the traction motor:

Table 9 – Parameter for IGBT Simulation Dynamic Load

Parameter	Nilai
Voltage (DC)	1500 V
Inverter : Snubber Resistance	10000 Ohm
Inverter : Snubber Capacitance	$1*10^{-6}$ F
Inverter : Ron	0,05 Ohm
Traction Motor	126 KW, 1100V, 74Hz
Stator (Resistance dan Inductance)	0.5968 Ohm, 0.0003495 H
Rotor (Resistance dan Inductance)	0.6258 Ohm, 0.005473 H

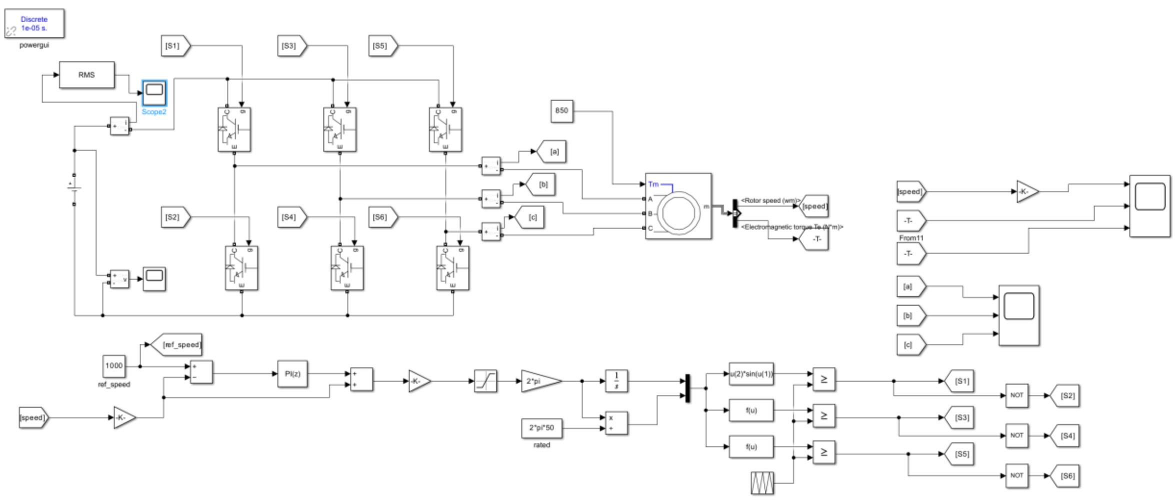

Figure 3. IGBT Dynamic Load Model

The switching performance simulation using IGBT with the traction motor load, as shown above, is presented in the following table:

Table 10 – IGBT Simulation Dynamic Load Result

Parameter	Hasil Simulasi
Voltage DC	1500 V
Input Current (depending on load applied)	102,9 A
Power Input	1500*102,9 = 154,350 KW
Motor Speed	1000 rpm = 104,72 rad/sec
Electric Motor Torque	850 Nm
Power Output	850*104,72 = 89,012 KW
Inverter Efficiency (power output / power input)	89,012 / 154,350 = 57,67 %

The simulation in this section uses a traction motor load, with an IGBT-based inverter. The test results show the efficiency percentage with the simulated load on the traction motor. The next simulation will use a SiC-based inverter, and the parameters used are as follows:

Table 11 – Parameter for SiC Simulation Dynamic Load

Parameter	Nilai
Voltage (DC)	1500 V
Inverter : Snubber Resistance	1000 Ohm
Inverter : Snubber Capacitance	$2*10^{-6}$ F
Inverter : Ron	0,0075 Ohm
Traction Motor	126 KW, 1100V, 74Hz
Stator (Resistance dan Inductance)	0.5968 Ohm, 0.0003495 H
Rotor (Resistance dan Inductance)	0.6258 Ohm, 0.005473 H

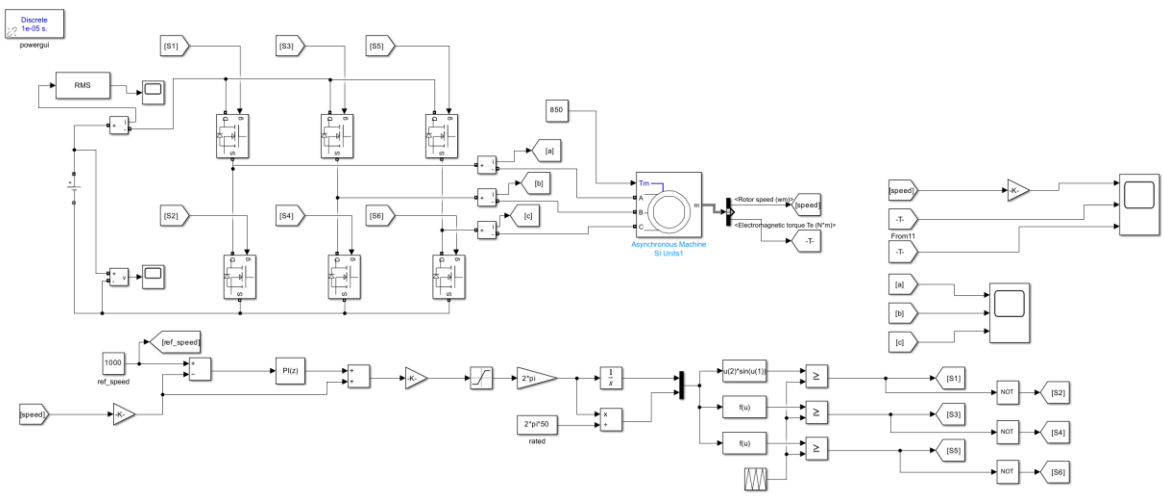

Figure 4. SiC Dynamic Load Model

The switching performance simulation using SiC with the traction motor load, as shown above, is presented in the following table:

Table 12 – SiC Simulation Dynamic Load Result

Parameter	Hasil Simulasi
Voltage DC	1500 V
Input Current (depending on load applied)	94,13 A
Power Input	1500*94,13 = 141,195 KW
Motor Speed	1000 rpm = 104,72 rad/sec
Electric Motor Torque	850 Nm
Power Output	850*104,72 = 89,012 KW (sama)
Inverter Efficiency (power output / power input)	89,012 / 141,195 = 63,04 %

The simulation in this section uses a traction motor load, but the inverter component is based on SiC. The test results show an efficiency of 63.04% with the simulated load on the traction motor. The comparison of efficiency between the simulations with the traction motor load is as follows:

Table 13 – Comparation of Simulation Dynamic Load Result

Components	**Power Output**	**Power Input**	**Input Current at DC Constant (1500VDC)**	**Inverter Efficiency**
IGBT	89,012 KW	154,350 KW	1500 V	57,67 %
SiC	89,012 KW	141,195 KW	1500 V	63,04 %

From the comparison results above, it can be observed that the output power is maintained at a constant level to allow for a comparison of the input power, which serves as the basis for calculating inverter efficiency. The inverter efficiency with the traction motor load using IGBT is 57.67%, while the efficiency with the SiC device is 63.04%.

4. CONCLUSION

MATLAB with SimPower Systems is capable of simulating the inverter propulsion model of the Jakarta Metro. Based on the simulation results, it is evident that the SiC-based inverter component is more energy efficient compared to the IGBT-based inverter. The detailed findings are as follows:

Static Load Simulation:

a. SiC is 1.34% more efficient under the same load conditions, resulting in a power reduction of 1,845 W to deliver 126 kW.
b. SiC achieves a 1.34% increase in efficiency that corresponds to a reduction in input current, assuming a stable input voltage, with a decrease of 1.23 A.
c. Efficiency increased from 95.02% (IGBT) to 96.36% (SiC) under identical load assumptions.

Dynamic Load Simulation:

a. SiC is 5.37% more efficient under dynamic load conditions, reducing input power by 13.155 kW to achieve the same 126 kW output.
b. SiC demonstrates a 5.37% efficiency gain impacting the input current, with a reduction of 8.77 A, assuming stable input voltage.
c. Efficiency improved from 57.67% (IGBT) to 63.04% (SiC) with the same dynamic load.

The simulation results indicate a significant efficiency improvement when using SiC as the switching component in traction motor inverters. The reduction in input current also has implications for the cooling system, potentially enhancing the durability and reducing the weight of the inverter components.

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