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Enhancing Metro Train Systems: A Comprehensive Analysis Of Regeneration Systems And Technological Advancements For Improved Energy Efficiency

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Abstract:
Amidst growing concerns over global energy demands and climate change, the transportation sector, particularly metro train systems, stands at the forefront of energy conservation efforts. This paper investigates the enhancement of energy efficiency in metro trains through the adoption of regenerative braking systems and the integration of Silicon Carbide (SiC) power devices. Focusing on traction, which accounts for 60-80% of a metro system's energy consumption, our study reveals the potential of regenerative braking to significantly reduce energy usage by approximately 20%. Further advancement is proposed with the transition to SiC technology, known for its superior thermal conductivity, electric field strength, and efficiency, offering a promising alternative to conventional silicon in power conversion devices. Our analysis underscores SiC's role in minimizing resistance loss and its impact on improving metro train performance and energy savings. This research highlights the critical need for innovative technological solutions in urban transportation to achieve greater energy efficiency and contribute to the reduction of greenhouse gas emissions. By showcasing the benefits of regenerative braking and SiC technology, we present a pathway towards sustainable urban mobility, emphasizing the importance of technological advancements in meeting global environmental commitments and enhancing metro train systems' energy conservation.

Key Word: *si based igbt devices; sic based mosfet devices; static (rl) load; dynamic (traction motor) load*

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I. Introduction

The relentless pursuit of a low-carbon society necessitates advancements in energy-efficient transportation solutions. The paper focuses on the critical need for energy-efficient transportation solutions to contribute to a low-carbon society and address global warming. It underlines the importance of reducing energy consumption and CO2 emissions in the transportation sector, particularly in metro and railway systems, through the adoption of electric traction systems with regeneration capabilities and the optimization of vehicle design. It notes the transportation sector's significant energy use and the rise in emissions, advocating for comprehensive strategies to minimize energy use from manufacturing to vehicle recycling. The paper also highlights the role of integrated, efficient public transport systems with electronic fare collection for seamless multi-modal travel. A key focus is on the advantages of silicon carbide (SiC) over traditional silicon in power electronics for transportation, given SiC's superior performance in terms of energy efficiency, voltage resistance, and thermal conductivity. SiC technology, especially in metro rail inverters, promises substantial energy savings and reduced greenhouse gas emissions through regenerative braking. The paper suggests leveraging new technologies like SiC to achieve compact, lightweight, and efficient power converters, meeting the strict demands of transportation applications for space, weight, and durability under harsh conditions. At present, Silicon carbide (SiC) is a superior semiconductor composed of silicon and carbon, offering advantages over traditional silicon, such as ten times higher dielectric breakdown field strength, a wider bandgap, and better thermal conductivity. This allows SiC devices to operate with much lower resistance at high voltages, significantly reducing it to 1/300th compared to silicon. SiC benefits MOSFETs by enabling high voltage, low resistance, and fast switching speeds due to its higher breakdown field and thermal reliability. SiC devices can also operate at higher temperatures, up to 200 degrees Celsius, compared to silicon's 150-175 degrees Celsius, making them ideal for demanding power electronics applications. The law of energy conservation states that energy cannot be created or destroyed, only changed from one form to another. In metro systems, this principle allows for the conversion of the electrical energy used to accelerate a train back into electrical energy during braking through regeneration with power electronics. However, in practice, only 20% to 40% of the input electrical energy is typically recovered during regeneration due to various losses. Metro operations, which often involve short distances between stations and frequent starts and stops, consume a significant amount of energy, with traction using about 60-80% of a metro system's total energy. The energy consumption of trains is affected by the network design, train design, and service operation. Therefore, optimizing the overall system design to reduce electricity consumption is crucial. Energy losses in the system can occur at various points, including the source level (OCS and RSS), between the OCS and converter, at the converter itself, due to limitations of power electronic devices, between the converter and the load, and at the load level (traction motors).

II. Literature Review And Problem Statement

Many articles and studies have been published about devices based on silicon carbide (SiC), their uses, and how they compare to traditional silicon (Si) based devices.

In a research paper, the authors presented Silicon Carbide (SiC) based devices advantages such as reduced thermal management needs and smaller passive components, leading to higher power density. They have higher blocking voltages, lower resistance and switching losses, and better thermal conductivity compared to silicon (Si) devices. SiC devices can operate at higher voltages, frequencies, and temperatures, resulting in lighter, smaller power converters and increased system efficiency.[1]

In another research paper proposes a method to determine the optimal switching frequency for maximizing efficiency in a railway propulsion system using a silicon carbide (SiC) inverter and permanent magnet synchronous motor (PMSM). The SiC power device's low switching power loss enables higher switching frequencies. Total system efficiency guides the selection of the SiC inverter's switching frequency, considering a hybrid switching method for PMSM control. Analysis results in an efficiency curve, facilitating the identification of the frequency with the minimum power loss to optimize system performance.[2]

The author of a paper designed a Successful field testing of a silicon carbide (SiC) metal-oxide-semiconductor field-effect transistor (MOSFET) traction inverter in the Stockholm metro system resulted in increased power density by 51% and volume and weight reductions by 25%. Lower power losses enabled car motion cooling and reduced sound pressure levels by 9 dB(A) with higher switching frequencies. Laboratory tests comparing silicon and SiC demonstrated a 19% reduction in propulsion system power losses with SiC, accompanied by acoustic noise reductions.[3]

In an earlier published research paper examines a PWM control strategy designed for SiC traction inverters to improve the running performance of traction motors across all speeds. The strategy combines asynchronous and optimal synchronous PWM control to minimize current harmonics. Experimental tests compared this approach to conventional methods, evaluating motor current quality, loss reduction, temperature rise, and noise suppression. Results confirm the effectiveness of the proposed PWM control strategy.[4]

In the literature, Researchers tested a new type of technology for train systems, using a material called silicon carbide (SiC) in a part known as a MOSFET traction inverter. They tried this out on a metro train in Stockholm's Green Line for three months. The results were impressive: the new technology made the train's power system much smaller (51% smaller) and lighter (22% lighter) than before. It also lost less power, which meant they could use a simpler cooling system. When they compared this new material (SiC) with the old one (silicon) in the lab, they found that SiC doesn't get as hot, especially when it's turned on and off at different speeds.[5]

III. Methodology

SiC based semiconductor materials have superior electrical characteristics compared with Si. Some of these characteristics for the most popular WBG semiconductors and Si are shown in Table no 1.

Table no 1: Physical characteristics of Si and the major WBG semiconductors.

Property	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 ($cm^2/V \cdot s$)	1,500	8,500	500	1,000	1,250	2,200
Hole mobility, μ_p ($cm^2/V \cdot s$)	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} ($\times 10^7$ cm/s)	1	1	2	2	2.2	2.7

The most important properties of the SiC-based semiconductors are explained in the following sections:

- High Saturated Drift Velocity
- Wide Bandgap

- High Thermal Stability
- High Electric Breakdown field

To transform the provided detailed comparison into a tabular format, we will summarize key points of comparison between SiC MOSFET and IGBT based traction inverters as simulated in PSIM, focusing on efficiency, cost, and energy losses under different load conditions and drive cycles.

Table no 2 : Comparison of Silicon Carbide MOSFET and IGBT based Electric Vehicle Traction Inverters

Aspect	SiC MOSFET Module (Cree CCS050M12CM2)	IGBT Module (Powerex PM50RL1A120)
Simulation Environment	PSIM	PSIM
Load Conditions	Varied to obtain efficiency curves	Varied to obtain efficiency curves
Efficiency Curves	Derived from simulation under different load conditions	Derived from simulation under different load conditions
Drive Cycles	Evaluated under three different drive cycles to estimate energy requirements	Evaluated under three different drive cycles to estimate energy requirements
Energy Losses	Compared based on simulations	Compared based on simulations
Cost Comparison	Included in evaluation but specific details need to be derived from simulation	Included in evaluation but specific details need to be derived from simulation
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 MOSFET
Technology	SiC (Silicon Carbide) based, offering inherent advantages over Si	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 EVs
Design Features	Incorporates an accumulation channel concept for improved performance	Standard design optimized for current EV applications
Simulation Environment	PSIM	PSIM

This table provides a structured overview of the simulation comparison between SiC MOSFET and IGBT modules for electric vehicle (EV) traction inverters, highlighting their performance under various conditions.

Based on the research literature review, I decided to investigate the MATLAB/Simulink environment with the SimPower systems block set for model development and simulations. It found that devices made of silicon carbide (SiC) are more energy-efficient and have lower losses than those made of silicon (Si).

IV. MATLAB Simulation Model & Performance Evaluation

(i) Performance Evaluation of Si based IGBT devices and SiC based MOSFET devices feeding Static (RL) load: It is assumed that Converter (from AC to DC) is supplying constant DC voltage thus directly DC Voltage source is taken for model building. Universal bridge is used in Inverter mode. LC filter, Current measuring device, Voltage measuring device, power measuring device and RL (static) load are modeled in MATLAB using Power System Block set.

Si based IGBT Inverter:

The parameters are as below:
DC Voltage = 1900 V
Inverter: Snubber resistance = 10000 Ohm
Snubber capacitance = $1 * 10^{-6}$ F
Ron (Ohm) = 0.05 Ohm
Ton time = $1.0 * 10^{-6}$ sec
Toff time = $2.0 * 10^{-6}$ sec
PWM Generator: Carrier frequency = 800 Hz
Modulation Index = 0.8
LC filter:L= $3 * 10^{-3}$ H
C= $100 * 10^{-6}$ F
RL Load= Equivalent to (200 KW *2) = 400 KW

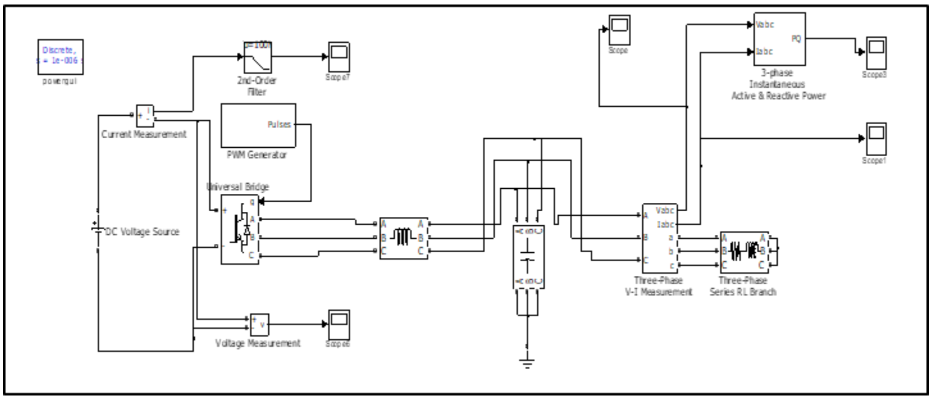

Figure 1: Simulink model for Static load (Si based IGBT)

Fig.1 depicts the setup used to study the performance of the Traction Inverter for Si based IGBT devices feeding Static load.
Input Voltage is fixed DC Link Voltage = 1900 V.
Input Current depends on load and corresponding input current = **217 Amps**.
Input Power = 900*217 = 412300 Watts= **412.3 KW**
Output Voltage Vpeak = 454 V
Voltage Vrms = 321 V
Output Current Ipeak = 589 Amps
Current Irms = 416.5 Amps
Active Power = 3.9 *10^5 Watts = **390 KW**
Inverter Efficiency = Output power / Input power
= 390/412.3
= **94.59 %**

<u>**SiC based MOSFET Inverter:**</u>
<u>The parameters are as below:</u>
DC Voltage = 1900 V
Inverter: Snubber resistance = 1000 Ohm
Snubber capacitance = 20 * 10^{-6} F
Ron (Ohm) = 0.0075 Ohm
Ton time = 4.5 * 10^{-9} sec
Toff time = 6.0 * 10^{-9} sec
PWM Generator: Carrier frequency = 10 KHz
Modulation Index = 0.8
LC filter: L= 1 * 10^{-3} H
C= 500 * 10^{-6} F
RL Load: = Equivalent to (200 KW * 2)
= 400 KW.
<u>The parameters are as below:</u>
DC Voltage = 1900 V
Inverter: Snubber resistance = 10000 Ohm
Snubber capacitance = 1 * 10^{-6} F
Ron (Ohm) = 0.05 Ohm
Ton time = 1.0 * 10^{-6} sec
Toff time= 2.0 * 10^{-6} sec
PWM Generator: Carrier frequency = 800 Hz
Modulation Index = 0.8
LC filter: L = 3 * 10^{-3} H
C = 100 * 10^{-6} F
RL Load: = Equivalent to (200 KW *2) = 400 KW

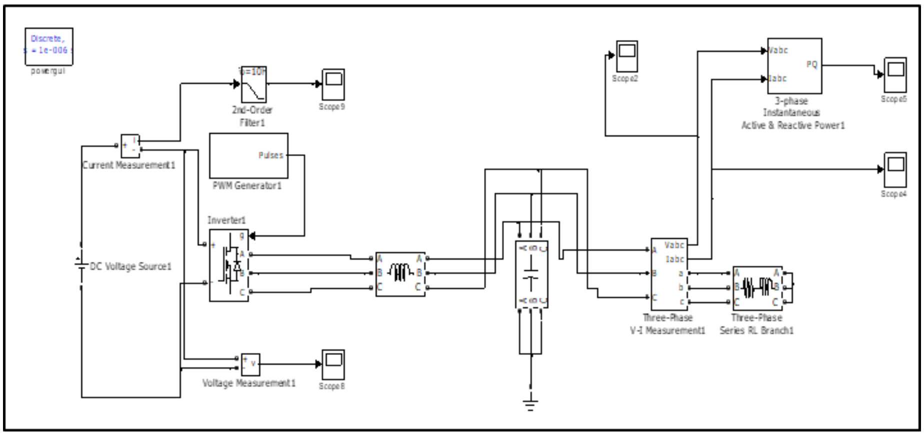

Figure 2: Simulink model for Static load (SiC based MOSFET)

Fig. 2 depicts the setup used to study the performance of the SiC based MOSFET devices feeding Static load.
Input Voltage is fixed DC Link Voltage = 1900 V.
Input Current depends on load and corresponding input current = **208 Amps**.
Input Power = 1900*208 = 395200Watts = **395.2KW**
Output Voltage Vpeak = 760 V
Voltage Vrms = 537.4 V
Output Current Ipeak = 350 Amps
Current Irms = 247. 50 Amps
Active Power = 3.9 * 10^5 Watts = **390 KW**

Inverter Efficiency = Output power / Input power
= 390/395.2
= **98.68 %**

Table no 3 : Summarized Result Table

Device	Output power (Load Requirement)	Input power (Required to meet load)	Input current at fixed DC link Voltage (1900 V)	Inverter Efficiency
Si based IGBT	390 KW	412.3 KW	217 Amps	94.59
SiC based MOSFET	390 KW (Same)	395.2 KW Reduction by 17.1 KW	208 Amps Reduction by 9 A	98.68

(ii) Performance Evaluation of Traction Motor (VVVF drive) with Si based IGBT device and with SiC based MOSFET device: It is assumed that Converter (from AC to DC) is supplying constant DC voltage thus directly DC Voltage source is taken for model building. Universal bridge is used in Inverter mode. LC filter, Current measuring device, Voltage measuring device, power measuring device and Traction Motor (Dynamic load) are modeled in MATLAB using Power System Block set. Motor is started initially with 100 Nm torque and later on torque is increased to 900 Nm.

<u>Si based IGBT Inverter:</u>
<u>The parameters are as below:</u>
DC Voltage = 1900 V
Inverter: Snubber resistance = 10000 Ohm
Snubber capacitance = 1 * 10^{-6} F
Ron (Ohm) = 0.05 Ohm
Ton time =1.0 * 10^{-6} sec
Toff time =2.0 * 10^{-6} sec
PWM Generator: Carrier frequency = 800 Hz
Modulation Index = 0.8

Traction Motor (Dynamic Load) = 220 KW, 1450 V,
72.5 Hz, 2% Slip
Stator Resistance = 0.1116 ohm
Inductance = 0.000317 H
Rotor Resistance = 0.1108 ohm

Inductance=0.000305H
Mutual Inductance = 0.0059 H

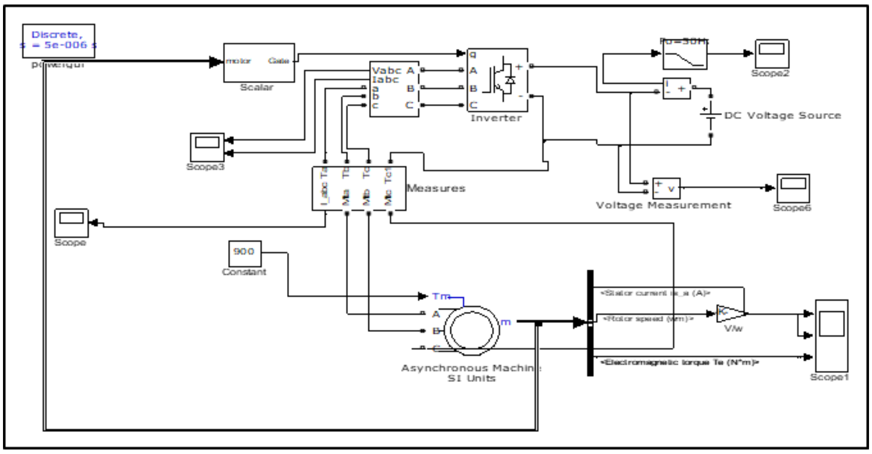

Figure 3: Simulink model for Traction Motor (Si based IGBT)

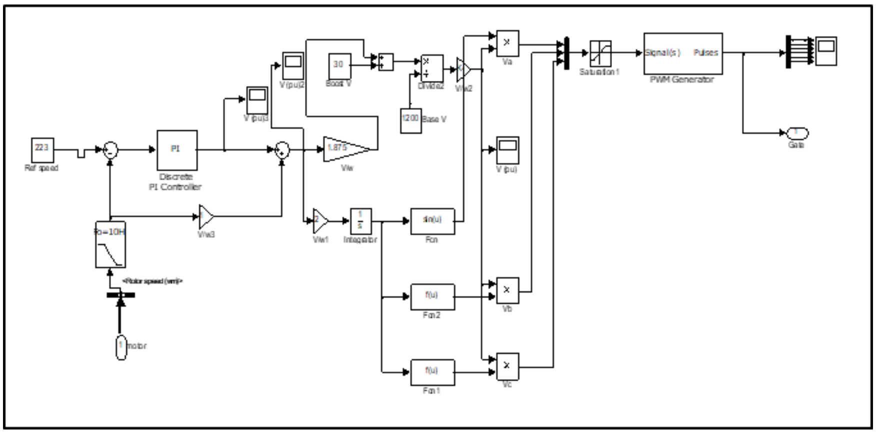

Figure 4: Simulink model for Control of VVVF drive (PWM for IGBT)

Fig. 3 and Fig. 4 depict the setup used to study the performance of the Traction Inverter for Si based IGBT devices feeding Traction Motor.
Input Voltage is fixed DC Link Voltage = 1900 V.
Input Current depends on load and corresponding input current = **118 Amps**.
Input Power = 1900 * 118 = 224200 Watts
= **224.20 KW**.
Input Voltage is fixed DC Link Voltage = 1900 V.
Input Current depends on load and corresponding input current = **118 Amps**.
Input Power = 1900 * 118 = 224200 Watts
= **224.20 KW**

SiC based MOSFET Inverter:

The parameters are as below:
DC Voltage = 1900 V
Inverter: Snubber resistance = 1000 Ohm
Snubber capacitance = 20 * 10^{-6} F
Ron (Ohm) = 0.0075 Ohm
Ton time = 4.5 * 10^{-9} sec
Toff time = 6.0 * 10^{-9} sec
PWM Generator: Carrier frequency = 10 KHz
Modulation Index = 0.8
Traction Motor (Dynamic Load): = 220 KW ,
1450 V, 72.5 Hz, 2% Slip
Stator Resistance = 0.1116 ohm

Inductance = 0.000317 H
Rotor Resistance = 0.1108 ohm
Inductance = 0.000305 H
Mutual Inductance = 0.0059 H

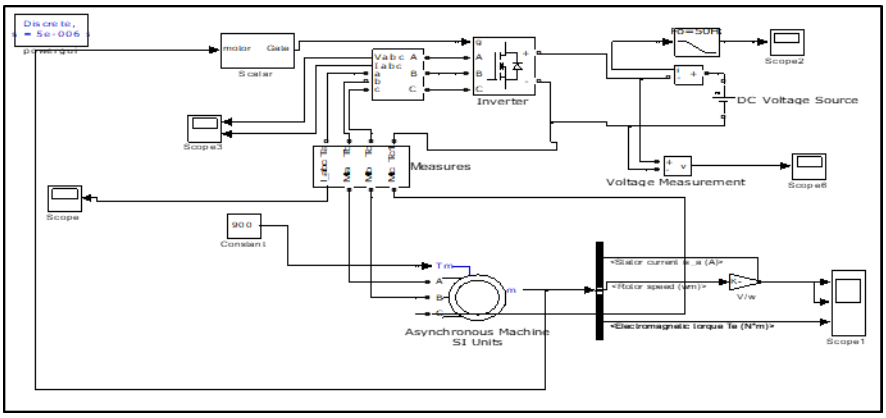

Figure 5: Simulink model for Traction Motor (SiC based MOSFET)

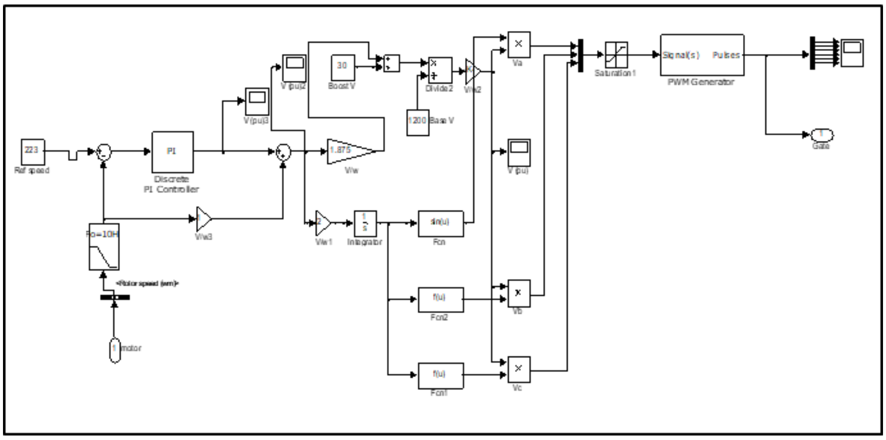

Figure 6: Simulink model for Control of VVVF drive (PWM for MOSFET)

Fig. 5 and Fig. 6 depict the setup used to study the performance of the SiC based MOSFET devices feeding Traction Motor.
Input Voltage is fixed DC Link Voltage = 1900 V.
Input Current depends on load and corresponding input current = **111 Amps**.
Input Power=1900 * 111= 210900Watts = **210.90 KW**
Stator Current Ipeak = 412 Amps
Current Irms = 291.33 Amps
Motor Speed = 2000 rpm = 209.44 rad/sec
Output Torque = 900 Nm
Output Torque = Torque * speed
= 900 * 209.44
= 188496 watts = **188.496 KW**

Inverter Efficiency (including Motor)
= Output power / Input power
=188.496/210.90
= **89.376 %**

Table no 4 : Summarized Result Table

Device	Output power (Load Requirement)	Input power (Required to meet load)	Input current at fixed DC link Voltage (1900 V)	Inverter Efficiency

Si based IGBT	188.496 KW	224.20 KW	118 Amps	84.075
SiC based MOSFET	188.496 KW (Same)	210.90 KW Reduction by 13.3 KW	111 Amps Reduction by 7 A	89.376

(iii) Performance Evaluation of Traction Motor (VVVF drive) in Regeneration mode with Si based IGBT device and with SiC based MOSFET device:

It is assumed that Converter (from AC to DC) is supplying constant DC voltage thus directly DC Voltage source is taken for model building. Universal bridge is used in Inverter mode. LC filter, Current measuring device, Voltage measuring device, power measuring device and Traction Motor (Dynamic load) are modeled in MATLAB using Power System Block set. Motor is started initially with 100 Nm torque and later on torque is increased to 900 Nm.

After start of Motor, the Motor is braked after 1 second and the Slope of speed getting reduced is calculated. The slope of Synchronous Speed is set higher than the slope of Motor Speed so that Motor is acting like a Generator.

Ns slope > N slope: N > Ns thus Motor is acting like Generator.

<u>Si based IGBT Inverter:</u>

<u>The parameters are as below:</u>

DC Voltage = 1900 V

Inverter: Snubber resistance = 10000 Ohm

Snubber capacitance = 1 X 10^{-6} F

Ron (Ohm) = 0.05 Ohm

Ton time =1.0 X 10^{-6} sec

Toff time =2.0 X 10^{-6} sec

PWM Generator: Carrier frequency = 800 Hz

Modulation Index = 0.8

Traction Motor (Dynamic Load): = 220 KW, 1450 V,

72.5 Hz, 2% Slip

Stator Resistance = 0.1116 ohm

Inductance = 0.000317 H

Rotor Resistance = 0.1108 ohm

Inductance = 0.000305 H

Mutual Inductance = 0.0059 H

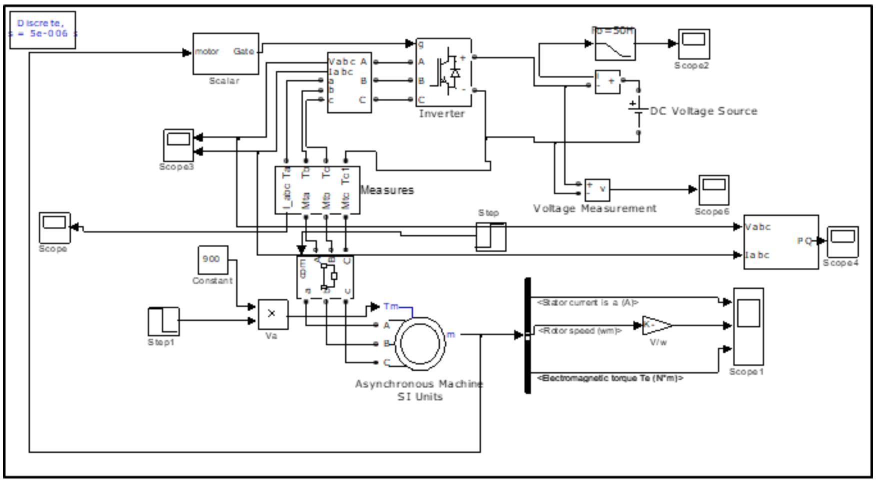

Figure 7: Simulink model for Traction Motor (Si based IGBT)

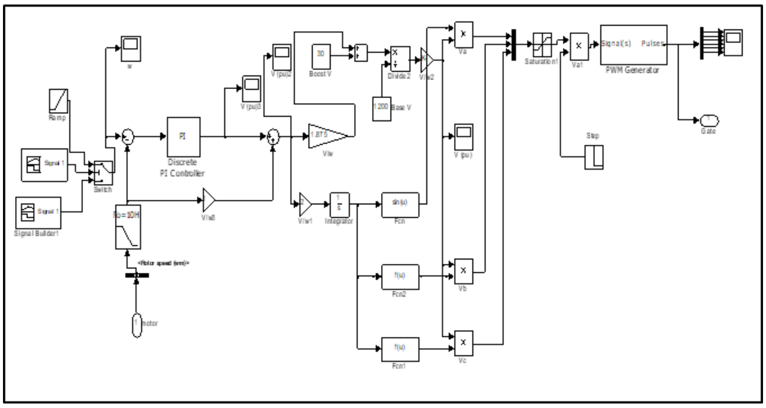

Figure 8: Simulink model for Control of VVVF drive (PWM for IGBT)

Fig. 7 and Fig. 8 depict the setup used to study the performance of the Traction Inverter for Si based IGBT devices feeding Traction Motor (in Regeneration mode).
Reduction of speed from 2000 rpm (209.44 rad/sec) to zero in approx. 0.014 seconds,
thus Slope = 209.44/0.014 = 14960
So fixed slope for Ns > 14960, thus
Fixed slope for Synchronous speed Ns, = 15000
Motor Speed = 2000 rpm = 209.44 rad/sec
Output Torque = 900 Nm

Regenerated Power (active) = 1390 Watts
<u>SiC based MOSFET Inverter:</u>
<u>The parameters are as below:</u>
DC Voltage = 1900 V
Inverter: Snubber resistance = 1000 Ohm
Snubber capacitance = 20 X 10^{-6} F
Ron (Ohm) = 0.0075 Ohm
Ton time = 4.5 X 10^{-9} sec
Toff time = 6.0 X 10^{-9} sec
PWM Generator: Carrier frequency = 10 KHz
Modulation Index = 0.8
Traction Motor (Dynamic Load) =220 KW,
1450 V, 72.5 Hz, 2% Slip
Stator Resistance = 0.1116 ohm
Inductance = 0.000317 H
Rotor Resistance = 0.1108 ohm
Inductance = 0.000305 H
Mutual Inductance = 0.0059 H

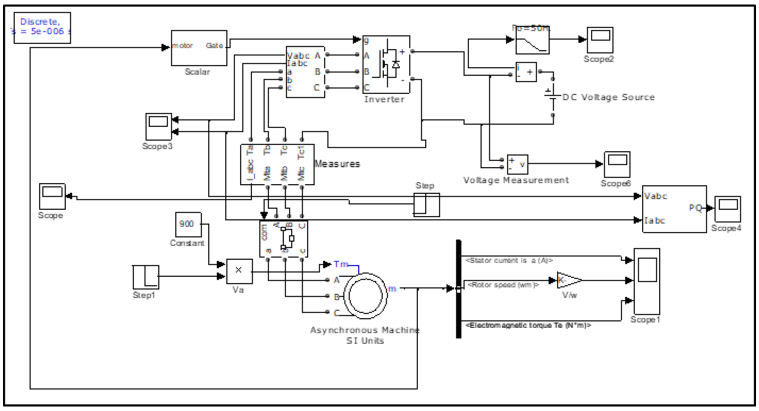

Figure 9: Simulink model for Traction Motor (SiC based MOSFET)

Device	Regenerated Power	Remarks
Si based IGBT	1390 Watts	Simulated for same load condition.
SiC based MOSFET	1550 Watts (**Saving of 160 Watts power)**	
% age saving	**11.51%**	

Table no 5: Summarized Result Table

Motor Speed = 2000 rpm = 209.44 rad/sec.
Output Torque = 900 Nm
Regenerated Power (active) = 1550 Watts.

V. Conclusion

The MATLAB/ Simulink environment using SimPower systems block set has been used to develop the model and carry out simulation work. It has been established by simulation that SiC based devices are more energy efficient and having very low losses compare to Si based devices.

<u>The conclusions drawn from result of Static (RL) Load are as below: -</u>

(i) Requirement of around 4.5 % less power for feeding of same load (reduction of 17.1 KW power for feeding of 390 KW).
(ii) Requirement of almost same %age 4.5% less current if Voltage is fixed (reduction of 9 Amps from 217 Amps).
(iii) Increase in efficiency from 94.59% (Si based IGBT) to 98.68% (SiC based MOSFET) for feeding same load.

<u>The conclusions drawn from result of Dynamic (Traction Motor) Load are as below: -</u>

(i) Requirement of around 5.9 % less power for feeding of same load (reduction of 13.3 KW power for feeding of 188.496 KW).
(ii) Requirement of almost same %age 5.9% less current if Voltage is fixed (reduction of 7 Amps from 118 Amps).
(iii) Increase in efficiency from 84.075% (Si based IGBT) to 89.376% (SiC based MOSFET) for feeding same load.

<u>The conclusions drawn from result of Regeneration mode (Traction Motor) are as below: -</u>

(i) Increase of Regeneration from 1390 Watts in Si based IGBT to 1550 Watts in SiC based MOSFET for same load condition.
(ii) Saving of Energy in terms of Regeneration is 11.51% (Increase of 160 Watts regeneration from original regeneration of 1390 Watts).

As a wide bandgap semiconductor technology, SiC allows greater efficiency and reliability than conventional Silicon devices. The significant improvement in efficiency delivers further advantages by allowing the size of any cooling systems and other motor-control components to be reduced. Overall, this can allow the size of the inverter to be reduced by as much as 40 %.

The use of SiC based device will result in Saving of Energy around 38% (55% of Switching losses alone). Conduction loss also gets reduced at a significant level.
Thus, it is recommended to use SiC based devices for Traction Controller.

VI. Future Scope of Work

This study was limited to only design improvement of Traction converter based on technological advancement; there are other factors also which determine the energy consumption of Train and energy efficiency.

The possible potential points for energy loss: -

1. **Source Level Losses (OCS and RSS):** Energy losses occurring at the Overhead Contact System (OCS) and the Rail Supply System (RSS).
2. **Losses Between OCS and Converter:** Energy dissipation during the transfer from OCS to the converter.
3. **Converter Level Losses:** Inefficiencies and energy losses at the converter itself.
4. **Limitations of Power Electronic Devices:** Identifying how the limitations of power electronic devices contribute to energy losses.
5. **Losses Between Converter and Load:** Energy losses during transmission from the converter to the load.
6. **Load Level Losses (Traction Motors):** Energy dissipation at the traction motors.

Out of the above possible points, only point 3 and 4 have been discussed and covered in this study.

There is a need to look at the entire factors in totality in conjunction with diversified and harsh requirement. This simulation needs to be put in practical field and to be evaluated practically before going into multiplication of same.

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