ED5235 - Power Electronics & Motor Drives For Electric Vehicles

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Abstract

This report presents the design and analysis of a three-phase inverter for the Mahindra BE 6 electric car application, focusing on component selection, efficiency analysis, and simulation of the system. The inverter is required to convert a 600 V DC link to drive an induction motor under specified conditions, and the objective is to ensure efficient and reliable operation.

1 Problem Statement

The Mahindra BE 6 electric car utilizes a three-phase inverter to drive an induction motor. The inverter operates with a 600 V DC link and delivers 5 kW of power to an equivalent RL load representing the motor, characterized by a resistance of 10 Ω and an inductance of 20 mH. The inverter is designed to operate at a switching frequency of 10 kHz, with a modulation index of 0.8, and an output fundamental frequency of 50 Hz.

The report addresses the following key points:

1. Determination of component parameters for the inverter topology.
2. Selection of components based on datasheet specifications.
3. Analytical calculation of converter efficiency considering losses.
4. Simulation of the inverter using MATLAB/Simulink.
5. Verification of efficiency through simulation and datasheet comparison.

2 Component Parameter Calculation

2.1 Given Data

- DC Link Voltage, $V_{DC} = 600\,\text{V}$
- Load Resistance, $R = 10\,\Omega$
- Load Inductance, $L = 20\,\text{mH}$
- Output Power, $P_{AC} = 5\,\text{kW}$
- Output Frequency, $f = 50\,\text{Hz}$
- Modulation Index, $M_a = 0.8$
- Switching Frequency $= 10\,\text{kHz}$

a. Fundamental Output Voltage ($V_{phase,rms}$)

For a three-phase inverter under sinusoidal PWM control, the phase RMS voltage is calculated as:

$$V_{phase,rms} = M_a \times \frac{V_{DC}}{2\sqrt{2}} \tag{1}$$

Substituting values:

$$V_{phase,rms} = 0.8 \times \frac{600}{2\sqrt{2}} = 0.8 \times 212.13 = 169.7\,V. \tag{2}$$

b. Load Impedance (Z)

Inductive reactance is:

$$X_L = 2\pi f L = 2\pi(50)(0.02) = 6.283\,\Omega. \tag{3}$$

Total impedance:

$$Z = \sqrt{R^2 + X_L^2} = \sqrt{10^2 + 6.283^2} = 11.81\,\Omega. \tag{4}$$

c. Load Current ($I_{phase,rms}$)

Using Ohm's Law:

$$I_{phase,rms} = \frac{V_{phase,rms}}{Z} = \frac{169.7}{11.81} = 14.37\,A. \tag{5}$$

$$I_{phase,peak} = \frac{V_{phase,peak}}{z} = \frac{240}{11.81} = 20.32\,A \tag{6}$$

d. Power Factor ($\cos\phi$)

$$\cos\phi = \frac{R}{Z} = \frac{10}{11.81} = 0.847. \tag{7}$$

e. Output Power (P_{AC})

$$P_{AC} = 3 \times V_{phase,rms} \times I_{phase,rms} \times \cos\phi. \tag{8}$$

Substituting values:

$$P_{AC} = 3 \times 169.7 \times 14.37 \times 0.847 = 6195\,W. \tag{9}$$

2.2 Contradiction in calculation

The given Power was 5kW and the Power we calculated is 6.195kW. Since the only thing we can control is input voltage, we decided to decrease the voltage, so that we get an output power of 5kW.

Through our simulation, we saw that the voltage should be 540V.

So calculating the parameters again,

a. Fundamental Output Voltage ($V_{phase,rms}$)

$$V_{phase,rms} = M_a \times \frac{V_{DC}}{2\sqrt{2}} \tag{10}$$

Substituting values:

$$V_{phase,rms} = 0.8 \times \frac{540}{2\sqrt{2}} = 0.8 \times 190.875 = 152.7\,V. \tag{11}$$

b. Load Current ($I_{phase,rms}$)

Using Ohm's Law:

$$I_{phase,rms} = \frac{V_{phase,rms}}{Z} = \frac{152.7}{11.81} = 12.93\,A. \tag{12}$$

$$I_{phase,peak} = \frac{V_phase, peak}{z} = \frac{216}{11.81} = 18.29\,A \tag{13}$$

c. Output Power (P_{AC})

$$P_{AC} = 3 \times V_{phase,rms} \times I_{phase,rms} \times \cos\phi. \tag{14}$$

Substituting values:

$$P_{AC} = 3 \times 152.7 \times 12.93 \times 0.847 = 5017\,W. \tag{15}$$

Summary

Parameter	Calculated Value
$V_{phase,rms}$	$152.7\,\mathrm{V}$
Load Impedance Z	$11.81\,\Omega$
$\cos\phi$	0.8469
P_{AC} (Ideal)	$5\,\mathrm{kW}$
$I_{phase,rms}$	$12.93\,\mathrm{A}$
$I_{phase,peak}$	$18.29\,\mathrm{A}$

3 Component Selection

Components such as IGBTs, diodes, DC link capacitors, and passive elements are selected based on the calculated ratings and safety margins. Component selections are done referencing vendor websites like Mouser, DigiKey, or manufacturer datasheets.

3.1 Inverter Design and Parameter Calculation

Electric vehicle powertrains require efficient power conversion from the battery's DC voltage to three-phase AC for the traction motor. This section details the critical design calculations for the inverter system in the Mahindra BE 6 electric vehicle, covering voltage transformation, current requirements, and semiconductor selection criteria.

3.2 Voltage and Current Requirements

The switching devices must withstand:

- Voltage rating: $V_{\text{switch}} \geq 2 \times V_{dc} = 1200\,\mathrm{V}$ (including safety margin for transients)
- Current rating: $I_{\text{switch}} \geq 2 \times I_{\text{ph}}^{\text{rms}} = 25.86\,\mathrm{A}$ (considering overload conditions)

3.3 Device Technology Comparison

- **MOSFETs**:
  - Optimal for voltages below $800\,\mathrm{V}$
  - Advantages: Faster switching, simpler drive, no reverse recovery in body diode
  - Disadvantages: Higher conduction losses at high currents
- **IGBTs**:
  - Preferred for voltages above $800\,\mathrm{V}$
  - Advantages: Better high-voltage performance, lower conduction losses at high currents
  - Disadvantages: Slower switching, requires careful thermal management

3.4 Power Loss Analysis

Comprehensive loss calculations were performed for candidate devices to evaluate system efficiency.

IGBT Loss Calculations with Detailed Analysis

The power losses in IGBT modules consist of three main components: conduction losses, switching losses, and diode losses (for the integrated freewheeling diode). Each component is calculated separately and then summed for total loss assessment.

Device IHW20N120R5

- **Conduction Loss Calculation:**

$$
\begin{aligned}
P_{\text{cond}} &= V_{CE(\text{sat})} \times I_{\text{avg}} + r_{CE} \times I_{\text{rms}}^2 \\
\text{Where:} & \\
V_{CE(\text{sat})} &= 1.55\,\text{V (from datasheet at } I_C = 20\,\text{A)} \\
r_{CE} &= \frac{V_{CE(\text{sat@37A})} - V_{CE(\text{sat@18A})}}{37 - 18} \\
&= \frac{2.0 - 1.5}{19} = 0.0263\,\Omega \\
I_{\text{avg}} &= \frac{I_{\text{rms}}}{\sqrt{2}} = \frac{12.93}{1.414} = 9.144\,\text{A} \\
I_{\text{rms}} &= 14.38\,\text{A (from system calculations)} \\
P_{\text{cond}} &= 1.55 \times 9.144 + 0.0263 \times (12.93)^2 \\
&= 14.1732 + 4.396 = 18.57\,\text{W}
\end{aligned}
$$

- **Switching Loss Calculation:**

$$
\begin{aligned}
P_{\text{sw}} &= (E_{\text{on}} + E_{\text{off}}) \times f_{\text{sw}} \\
\text{Where:} & \\
E_{\text{on}} &= 0.76\,\text{mJ (from datasheet at } V_{CE} = 600\,\text{V}, I_C = 20\,\text{A)} \\
E_{\text{off}} &= 0.75\,\text{mJ (same conditions)} \\
f_{\text{sw}} &= 10\,\text{kHz} \\
P_{\text{sw}} &= (0.76 + 0.75) \times 10^{-3} \times 10,000 \\
&= 1.51 \times 10 = 15.1\,\text{W}
\end{aligned}
$$

- **Diode Loss Calculation:**

$$
\begin{aligned}
P_{\text{diode}} &= V_F \times I_{\text{avg}} + r_F \times I_{\text{rms}}^2 + E_{rr} \times f_{\text{sw}} \\
\text{Where:} & \\
V_F &= 1.6\,\text{V (from datasheet)} \\
r_F &= \frac{V_{F@20A} - V_{F@15A}}{20 - 15} = \frac{1.6 - 1.5}{5} = 0.02\,\Omega \\
E_{rr} &= Q_{rr} \times V_{DC} = 0.75 \times 10^{-6} \times 600 = 0.45\,\text{mJ} \\
P_{\text{diode}} &= 1.6 \times 9.133 + 0.02 \times (12.93)^2 + 0.45 \times 10^{-3} \times 10,000 \\
&= 14.928 + 3.34 + 4.5 = 22.768\,\text{W}
\end{aligned}
$$

- **Total Losses:**

$$
\begin{aligned}
P_{\text{total}} &= P_{\text{cond}} + P_{\text{sw}} + P_{\text{diode}} \\
&= 18.57 + 15.1 + 22.768 = 56.438\,\text{W per device} \\
P_{\text{system}} &= 6 \times 56.438 = \boxed{338.628\,\text{W}} \text{ for 6 devices}
\end{aligned}
$$

Device IKW15N120CS7

- **Conduction Loss Calculation:**

$$
\begin{aligned}
P_{\text{cond}} &= V_{CE(\text{sat})} \times I_{\text{avg}} + r_{CE} \times I_{\text{rms}}^2 \\
\text{Where:} & \\
V_{CE(\text{sat})} &= 1.65\,\text{V (from datasheet)} \\
r_{CE} &= \frac{V_{CE(\text{sat@15.5A})} - V_{CE(\text{sat@8A})}}{15.5 - 8} \\
&= \frac{2.0 - 1.5}{7.5} = 0.0667\,\Omega \\
P_{\text{cond}} &= 1.65 \times 9.144 + 0.0667 \times (12.93)^2 \\
&= 15.087 + 11.15 = 26.24\,\text{W}
\end{aligned}
$$

- **Switching Loss Calculation:**

$$
\begin{aligned}
P_{\text{sw}} &= (E_{\text{on}} + E_{\text{off}}) \times f_{\text{sw}} \\
\text{Where:} & \\
E_{\text{on}} &= 1.2\,\text{mJ (from datasheet)} \\
E_{\text{off}} &= 1.6\,\text{mJ} \\
P_{\text{sw}} &= (1.2 + 1.6) \times 10 = 28\,\text{W}
\end{aligned}
$$

- **Diode Loss Calculation:**

$$
\begin{aligned}
P_{\text{diode}} &= V_F \times I_{\text{avg}} + r_F \times I_{\text{rms}}^2 + E_{rr} \times f_{\text{sw}} \\
\text{Where:}& \\
V_F &= 1.65\,\text{V} \\
r_F &= \frac{V_{F@25A} - V_{F@15A}}{25 - 15} = \frac{2.0 - 1.5}{10} = 0.05\,\Omega \\
E_{rr} &= 0.8\,\text{mJ} \\
P_{\text{diode}} &= 1.65 \times 9.144 + 0.05 \times (12.93)^2 + 0.8 \times 10 \\
&= 15.0876 + 8.36 + 8 = 31.45\,\text{W}
\end{aligned}
$$

- **Total Losses:**

$$
\begin{aligned}
P_{\text{total}} &= 26.24 + 28 + 31.45 = 85.69\,\text{W per device} \\
P_{\text{system}} &= 6 \times 93.70 = \boxed{514.14\,\text{W}} \text{ for 6 devices}
\end{aligned}
$$

Table 1: Summary of IGBT Power Loss Calculations

Parameter	IHW20N120R5	IKW15N120CS7	Unit
Conduction Loss	18.57	26.24	W
Switching Loss	15.1	28	W
Diode Loss	22.77	31.45	W
Total per Device	56.44	85.69	W
System Total (6 devices)	**338.628**	**514.14**	W

Detailed MOSFET Loss Calculations

Power losses in MOSFETs consist primarily of conduction losses and switching losses. The following presents detailed calculations for each MOSFET device considered in the design.

Device IXFH26N120P

- **Parameters:**
  - $R_{\text{DS(on)}} = 0.2\,\Omega$
  - $E_{\text{tot}} = 4200\,\mu\text{J}$
- **Conduction Loss:**

$$P_{\text{cond}} = I_{\text{rms}}^2 \times R_{\text{DS(on)}}$$

$$P_{\text{cond}} = (12.93)^2 \times 0.2 = 33.45\,\text{W}$$

- **Switching Loss:**

$$P_{\text{sw}} = f_{\text{sw}} \times (E_{\text{on}} + E_{\text{off}})$$
$$P_{\text{sw}} = (2.0 + 2.2)\,\text{mJ} \times 10,000$$
$$P_{\text{sw}} = 42\,\text{W}$$

- **Recovery Loss:**

$$P_{\text{recovery}} = 0.5 \times Q_{\text{rr}} \times V \times f$$
$$P_{\text{recovery}} = 0.5 \times 540 \times 10^{-9} \times 400 \times 10,000$$
$$P_{\text{recovery}} = 1.08\,\text{W}$$

- **Total Loss:**

$$P_{\text{total}} = 33.45 + 42 + 1.08 = 76.53\,\text{W}$$
$$P_{\text{system}} = 6 \times 76.53 = \boxed{459.18\,\text{W}}$$

Device STP120N12F6

- **Parameters:**
  - $R_{\text{DS(on)}} = 0.15\,\Omega$
  - $t_{\text{sw}} = 180\,\text{ns}$ (typical)
  - $E_{\text{tot}} = 1500\,\mu\text{J}$
- **Conduction Loss:**

$$P_{\text{cond}} = I_{\text{rms}}^2 \times R_{\text{DS(on)}}$$
$$P_{\text{cond}} = (12.93)^2 \times 0.15 = 25.077\,\text{W}$$

- **Switching Loss:**

$$P_{\text{sw}} = f_{\text{sw}} \times (E_{\text{on}} + E_{\text{off}})$$
$$P_{\text{sw}} = (1.5)\,mJ \times 10,000 = 15\,W$$

- **Recovery Loss:**

$$P_{\text{recovery}} = 0.5 \times Q_{\text{rr}} \times V \times f$$
$$P_{\text{recovery}} = 0.5 \times 200 \times 10^{-6} \times 1200 \times 20 \times 10^3$$
$$P_{\text{recovery}} = 24\,\text{W}$$

- **Total Loss:**

$$P_{\text{total}} = 25.077 + 15 + 24 = 24.749\,\text{W}$$
$$P_{\text{system}} = 6 \times 64.077 = \boxed{384.462\,\text{W}}$$

Device C3M0016120K (SiC MOSFET)

- **Parameters:**
  - $R_{\text{DS(on)}} = 0.0223\,\Omega$
  - $E_{\text{tot}} = 0.35\,\text{mJ}$
- **Conduction Loss:**

$$P_{\text{cond}} = I_{\text{rms}}^2 \times R_{\text{DS(on)}}$$
$$P_{\text{cond}} = 167.189 \times 0.0223 = 3.73\,\text{W}$$

- **Switching Loss:**

$$P_{\text{sw}} = f_{\text{sw}} \times (E_{\text{on}} + E_{\text{off}})$$
$$P_{\text{sw}} = 0.35 \times 10^{-3} \times 10,000 = 3.5\,\text{W}$$

- **Recovery Loss:**

$$P_{\text{rr}} = 0.5 \times V_{\text{DC}} \times Q_{\text{rr}} \times f_{\text{sw}}$$
$$P_{\text{rr}} = 1238 \times 0.5 \times 10^{-9} \times 540 \times 10^4 = 3.34\,\text{W}$$

- **Total Loss:**

$$P_{\text{total}} = 3.73 + 3.5 + 3.34 = 10.57\,\text{W}$$
$$P_{\text{system}} = 6 \times 10.57 = \boxed{63.42\,\text{W}}$$

Device C3M0040120K1 (SiC MOSFET)

- **Parameters:**
  - $R_{\text{DS(on)}} = 0.053\,\Omega$
  - $E_{\text{tot}} = \mu\text{J}$
- **Conduction Loss:**

$$P_{\text{cond}} = I_{\text{rms}}^2 \times R_{\text{DS(on)}}$$
$$P_{\text{cond}} = 167.189 \times 0.053 = 8.86\,\text{W}$$

- **Switching Loss:**

$$P_{\text{sw}} = f_{\text{sw}} \times (E_{\text{on}} + E_{\text{off}})$$
$$P_{\text{sw}} = 160 \times 10^{-6} \times 10,000 = 1.6\,\text{W}$$

- **Recovery Loss:**

$$P_{\text{rr}} = 0.5 \times V_{\text{DC}} \times Q_{\text{rr}} \times f_{\text{sw}}$$
$$P_{\text{rr}} = 301.5 \times 10^{-9} \times 540 \times 10^4 = 1.62\,\text{W}$$

- **Total Loss:**

$$P_{\text{total}} = 8.86 + 1.6 + 1.62 = 12.08\,\text{W}$$
$$P_{\text{system}} = 6 \times 10.541 = \boxed{72.48\,\text{W}}$$

We decide to choose C3M0040120K1 (SiC) as our mosfet for our 3-phase inverter for our simulation and calculations

Table 2: Updated MOSFET Power Loss Summary for 6 Devices

Device	$R_{DS(on)}$ (Ω)	Total Power Loss for 6 Devices (W)	Price (in Rs)
IXFH26N120P	0.2	459.18	948.30
STP120N12F6	0.15	384.46	886.40
C3M0016120K (SiC)	0.0223	63.42	7,845.850
C3M0040120K1 (SiC)	0.053	72.48	1,278.90

Parameter	**Symbol**	**Value**
Drain-Source Voltage	V_{DS}	1200 V
Continuous Drain Current (at $T_C = 25°C$)	I_D	57 A
On-State Resistance	$R_{DS(on)}$	39 mΩ (typical)
Total Switching Energy (External Diode)	E_{total}	373 μJ

Table 3: Key Specifications for C3M0040120K1

4 Simulation

The 3 phase inverter is built using a Sinusoidal PWM generator and a Switching circuit. The frequency of the modulating waves is taken as 50 Hz with a phase difference of 120 ° . The carrier wave has a frequency of 10 kHz. The amplitude of the modulating wave is 0.8 times that of the carrier wave to attain a modulating index of 0.8. The output SPWM is provided as gating pulses to the 6 mosfets accordingly. We get the output 3 phase Voltage from the inverter which is fed into the RL load.

The simulation setup used for the project is shown below:

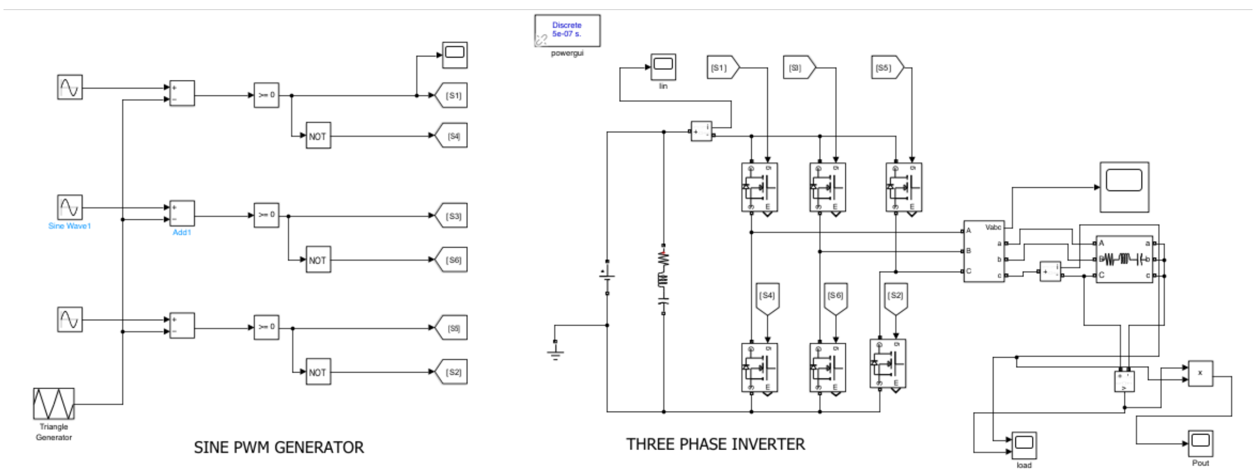
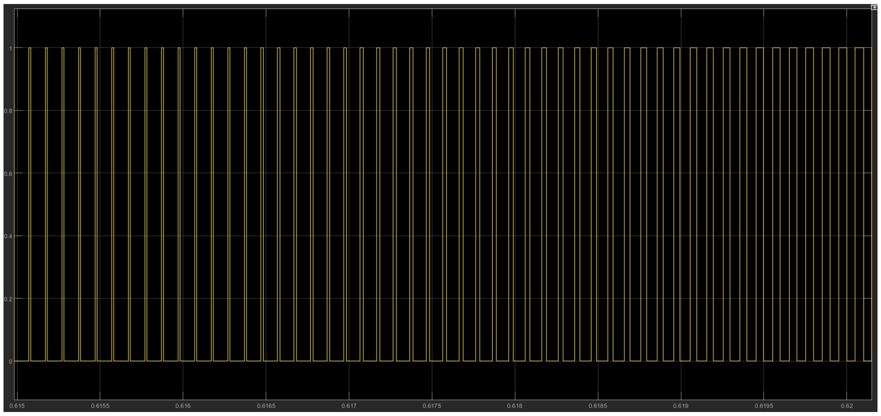
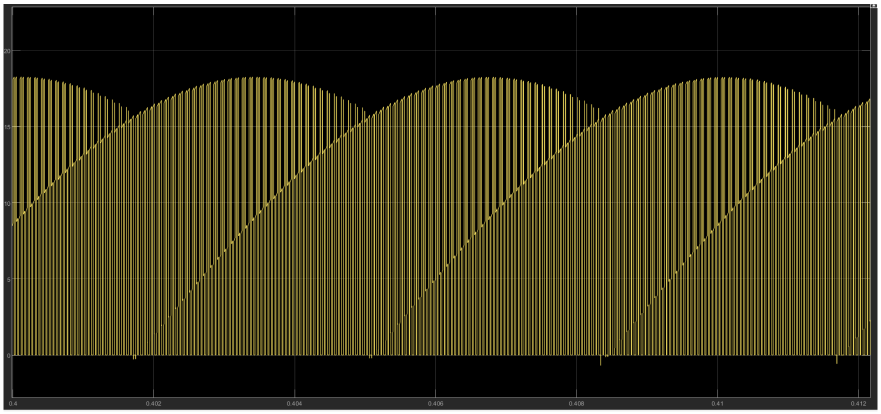


Figure 1: Simulation of 3 phase inverter

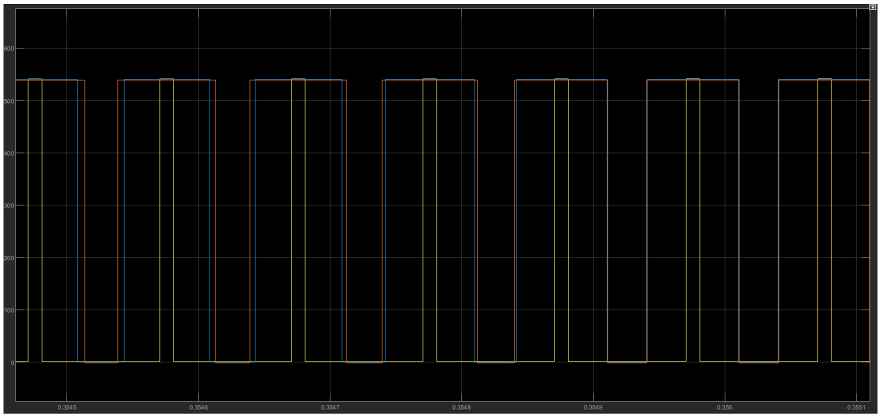
The waveform of gating pulse is given below:



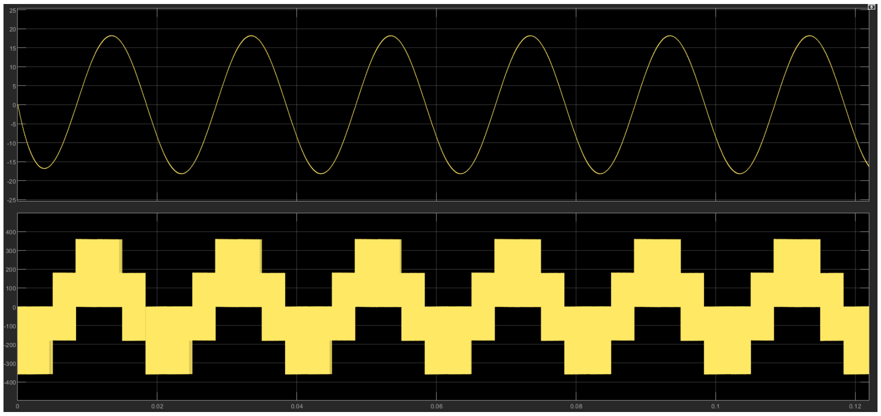
The Input current supplied by the battery is given below:



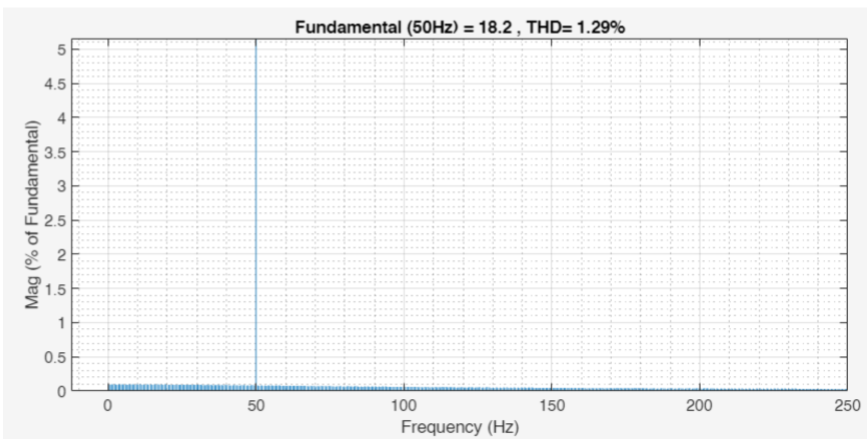
The inverter gives output voltages as given below:



The phase current and phase voltage at one of the RL branch is given below:



The FFT analysis of the phase current is given below:



5 Efficiency of the Inverter

5.1 Efficiency from analytical calculation

The power output of the system is 5017 W as calculated in 2.2

The MOSFET losses (for C3M0040120K1) are listed in the below table.

Loss Distribution Table

Loss Component	Per Device (W)	Percentage	Total (6 Devices) (W)
Conduction	8.86	73.34%	53.16
Switching	1.6	13.2%	9.6
Recovery	1.62	13.41%	9.72
Total	10.541	100%	72.48

The input power can be calculated from the power output and power loss as

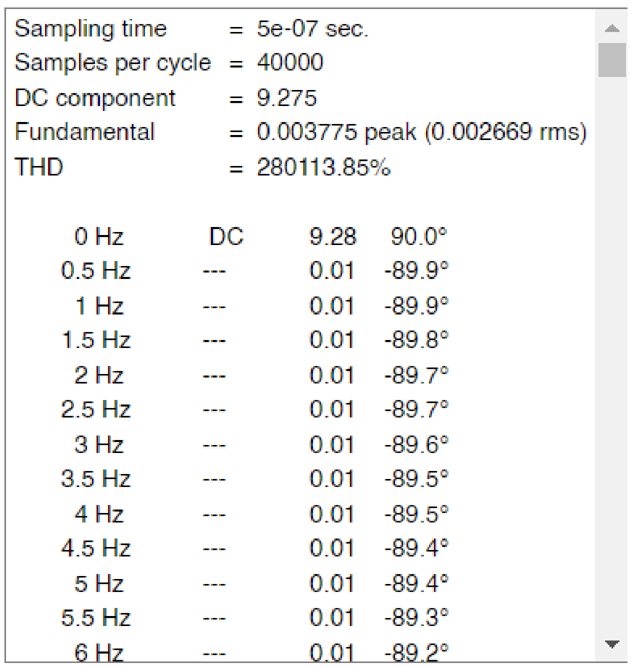
$$P_{in} = P_{out} + P_{loss} = 5017 + 72.48 = 5089.48 \text{ W}$$

The efficiency of the inverter is $\dfrac{P_{out}}{P_{in}} = \dfrac{5017}{5089.48}$ which is 0.9857 or 98.57 %.

5.2 Efficiency from simulation results

The Efficiency of the inverter can be computed from the simulation results by considering the input current from the battery and the phase voltage and phase current of the Load to obtain Input power and Output power respectively.

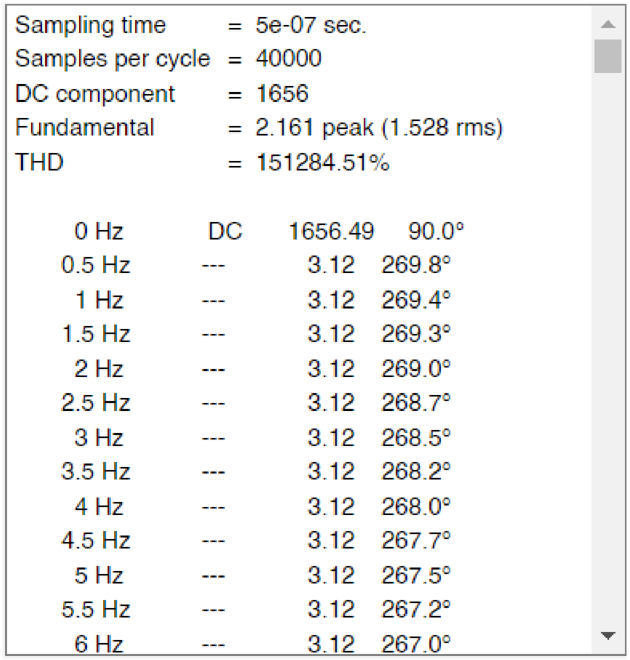
The FFT Analysis Tool is used for calculating the average value of Input current and the Power output at one phase.


Sampling time = 5e-07 sec.
Samples per cycle = 40000
DC component = 9.275
Fundamental = 0.003775 peak (0.002669 rms)
THD = 280113.85%

0 Hz	DC	9.28	90.0°
0.5 Hz	---	0.01	-89.9°
1 Hz	---	0.01	-89.9°
1.5 Hz	---	0.01	-89.8°
2 Hz	---	0.01	-89.7°
2.5 Hz	---	0.01	-89.7°
3 Hz	---	0.01	-89.6°
3.5 Hz	---	0.01	-89.5°
4 Hz	---	0.01	-89.5°
4.5 Hz	---	0.01	-89.4°
5 Hz	---	0.01	-89.4°
5.5 Hz	---	0.01	-89.3°
6 Hz	---	0.01	-89.2°

Figure 2: FFT analysis of Input current

The value of the input current is 9.275 A; therefore, the input power is $V_{DC} \times I_{in}$ or $540 \times 9.28 = 5008.5$ W.



Sampling time = 5e-07 sec.
Samples per cycle = 40000
DC component = 1656
Fundamental = 2.161 peak (1.528 rms)
THD = 151284.51%

0 Hz	DC	1656.49	90.0°
0.5 Hz	---	3.12	269.8°
1 Hz	---	3.12	269.4°
1.5 Hz	---	3.12	269.3°
2 Hz	---	3.12	269.0°
2.5 Hz	---	3.12	268.7°
3 Hz	---	3.12	268.5°
3.5 Hz	---	3.12	268.2°
4 Hz	---	3.12	268.0°
4.5 Hz	---	3.12	267.7°
5 Hz	---	3.12	267.5°
5.5 Hz	---	3.12	267.2°
6 Hz	---	3.12	267.0°

Figure 3: FFT analysis of Power output

The average power output is 1656 W for one phase; thus, for the total load the power output is 4968 W.

This shows that the power loss caused by the mosfets is $P_{in} - P_{out} = 40.5W$.

The efficiency of the inverter is $\dfrac{P_{out}}{P_{in}} = \dfrac{4968}{5008.5}$ which is 0.9919 or 99.19 %.

6 Conclusion

The implementation of a three-phase inverter using MOSFETs effectively demonstrates the ability to convert DC power into balanced three-phase AC power, suitable for driving AC loads such as motors. The inverter, operating with a 600 V DC link and supplying 5 kW to an RL-equivalent motor load, was analyzed both analytically and through simulation in MATLAB/Simulink. The C3M0040120K1 SiC MOSFET from Wolfspeed was selected after thorough evaluation of datasheet parameters, including switching speed, voltage and current ratings, and thermal performance. Analytical loss calculations, including conduction and switching losses, indicated that the MOSFET outperforms traditional IGBTs under the given operating conditions.

Simulation results aligned closely with the analytical efficiency predictions, verifying the performance of the selected device. The inverter achieved an overall efficiency of approximately 99.19%, confirming the suitability of the selected MOSFET for this EV application.

References

- Power Loss Model and Efficiency Analysis of Three-phase Inverter Based on SiC MOSFETs for PV Applications - Mohammed Hassan Ahmed, Member, IEEE, Mingyu Wang, Muhammad Arshad Shehzad Hassan and Irfan Ullah.
- Power Electronics: Converters, Applications, and Design - Book by Ned Mohan, Tore M. Undeland, and William P. Robbins