ED5235- POWER ELECTRONICS AND MOTOR DRIVES FOR ELECTRIC VEHICLES

PROBLEM 7- DESIGN OF 3-PHASE INVERTER

Group 7
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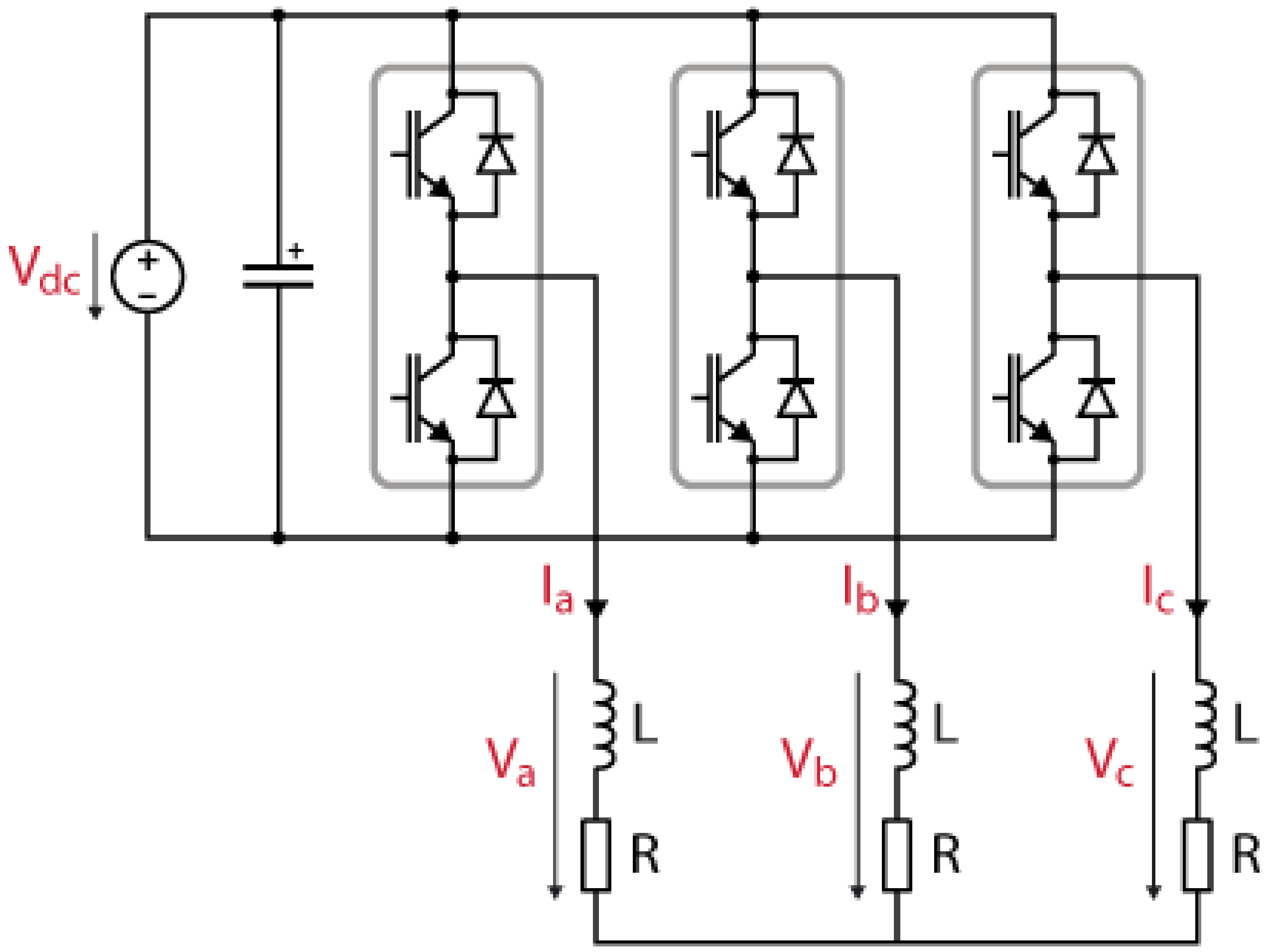
Problem Statement - Problem 7

The Mahindra BE 6 electric car utilizes a three-phase inverter that drives an induction motor in power applications. The inverter is connected to a 600 V DC link, delivering 5 kW of power to an equivalent load with 10 Ω resistance and 20 mH inductance (assuming equivalent RL-load for induction motor here). The design engineer suggested operating the inverter at 10 kHz with a modulation index of 0.8. The fundamental frequency of the output is 50 Hz.

(a) Determine the component parameters for the inverter topology.
(b) Select the components for the converter based on the datasheets. [Hint: Refer to Mouser or DigiKey or any other websites to select components based on voltage and current ratings]
(c) Corresponding to the component selected, calculate the losses and calculate the analytical efficiency of the power converter.
(d) Simulate the converter in MATLAB or any other suitable software and report the required waveforms.
(e) From the simulation results, calculate the power converter's efficiency based on the datasheet for the selected component.

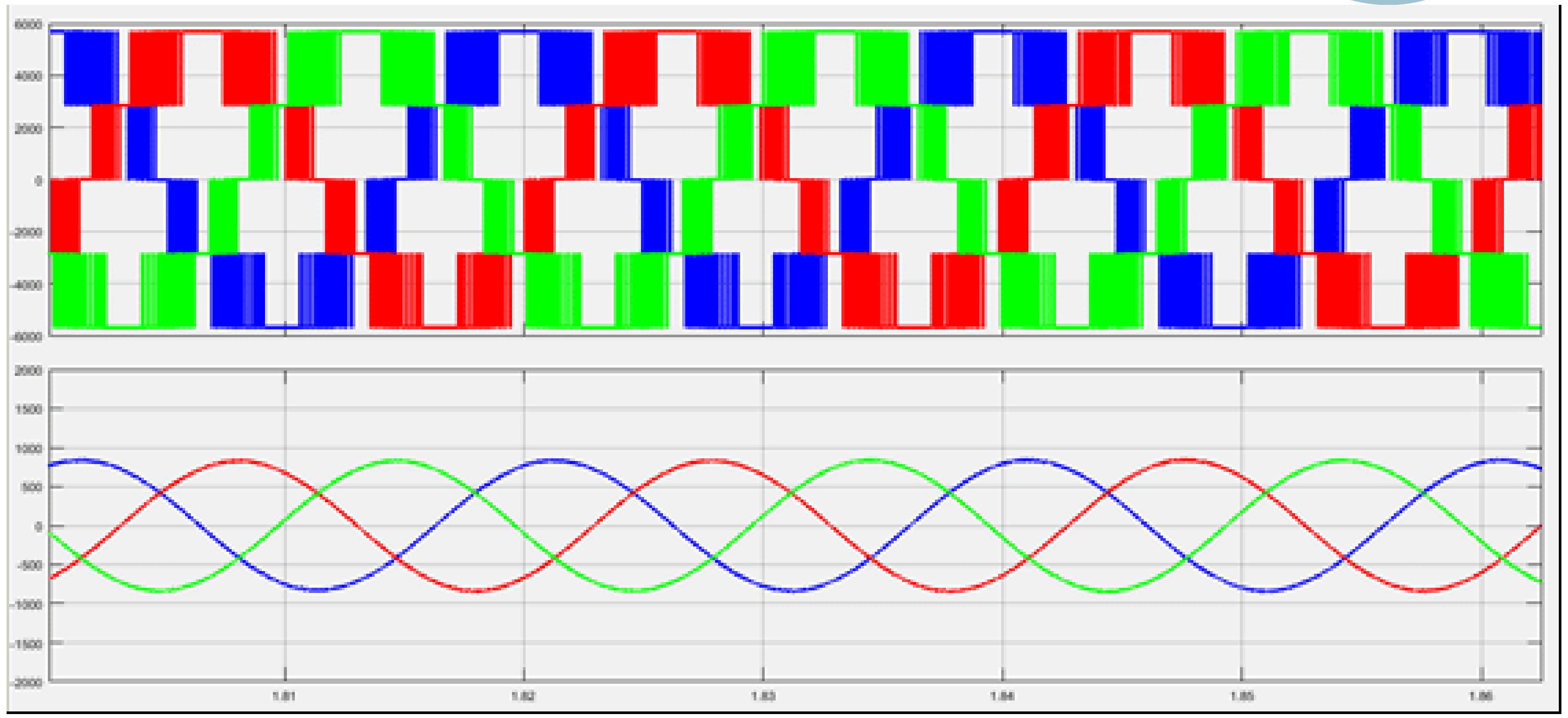
What is an INVERTER?

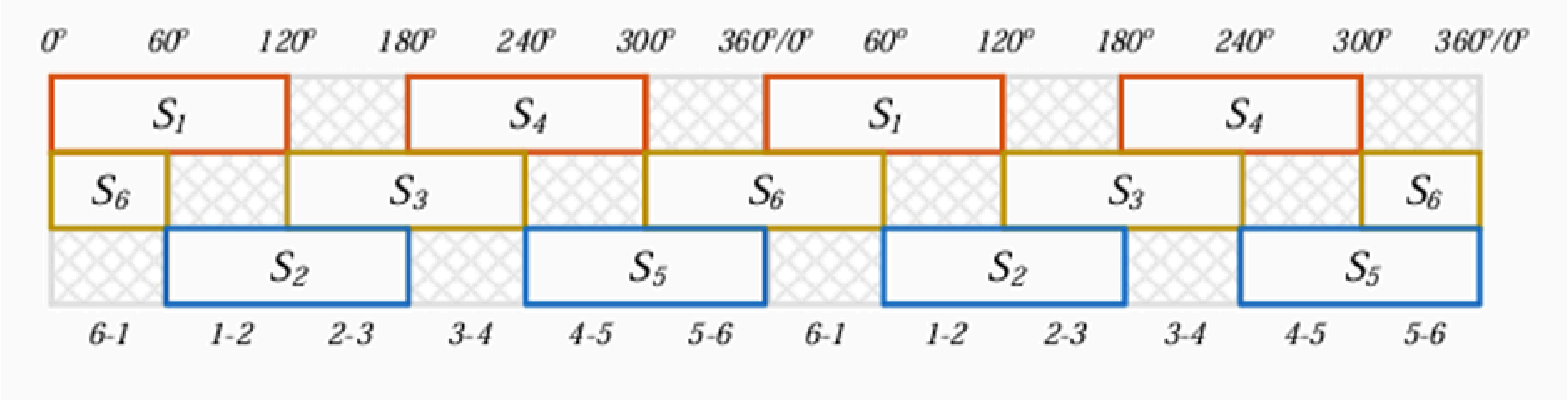
- An inverter is an electronic device that converts DC (Direct Current) into AC (Alternating Current).
- In electric vehicles, the battery stores energy as DC (Direct Current), but EV motors require 3-phase AC (Alternating Current) to run efficiently.
- Inverters utilize a switching circuit and control for the switches to convert DC to AC.



Why 3-PHASE

- Provides smooth and continuous torque output — no vibration or jerks.
- More efficient power delivery compared to single-phase.
- Compact motor design: Motors are smaller and lighter for the same power.
- Better torque control across all speeds, which is crucial for driving conditions

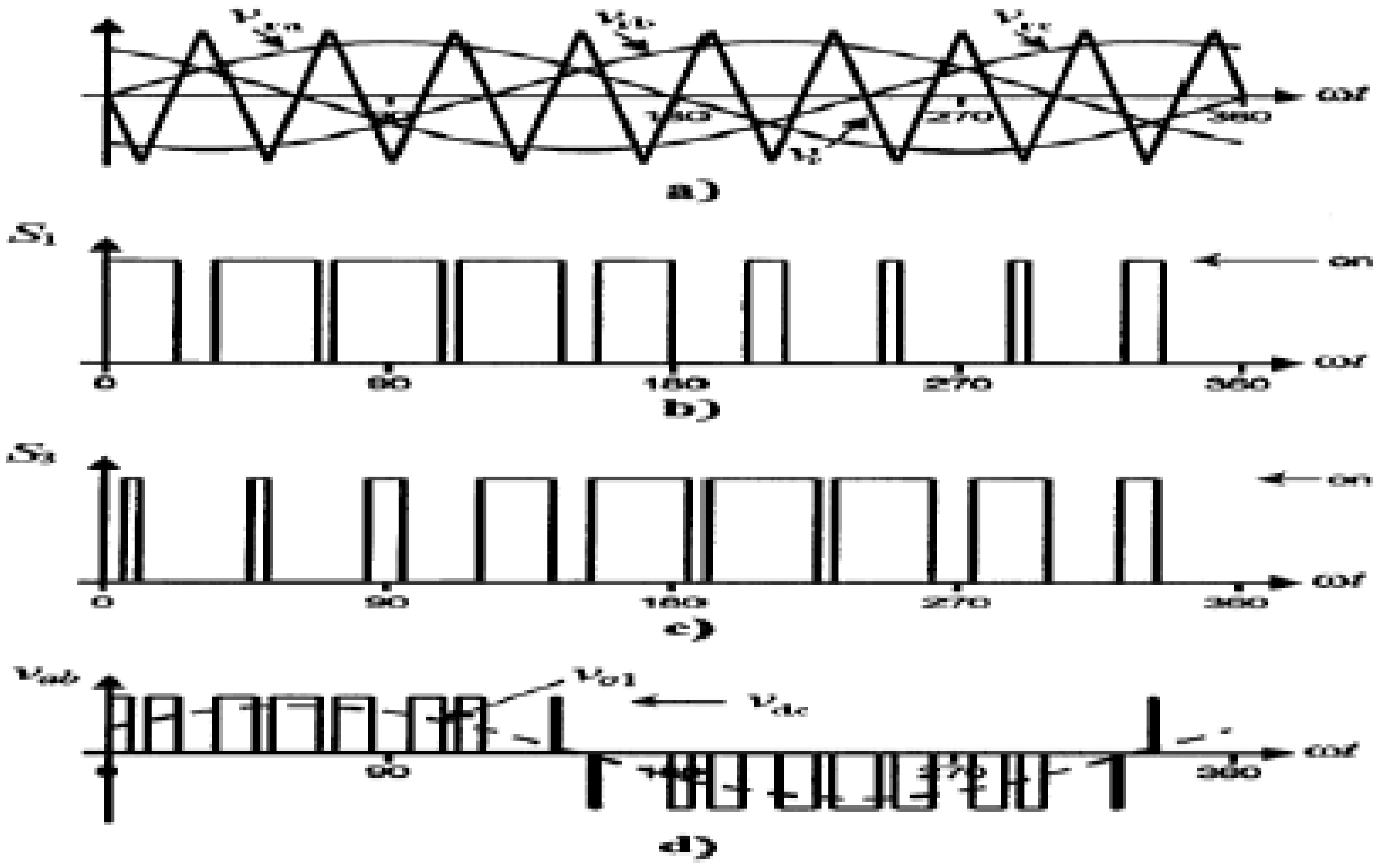


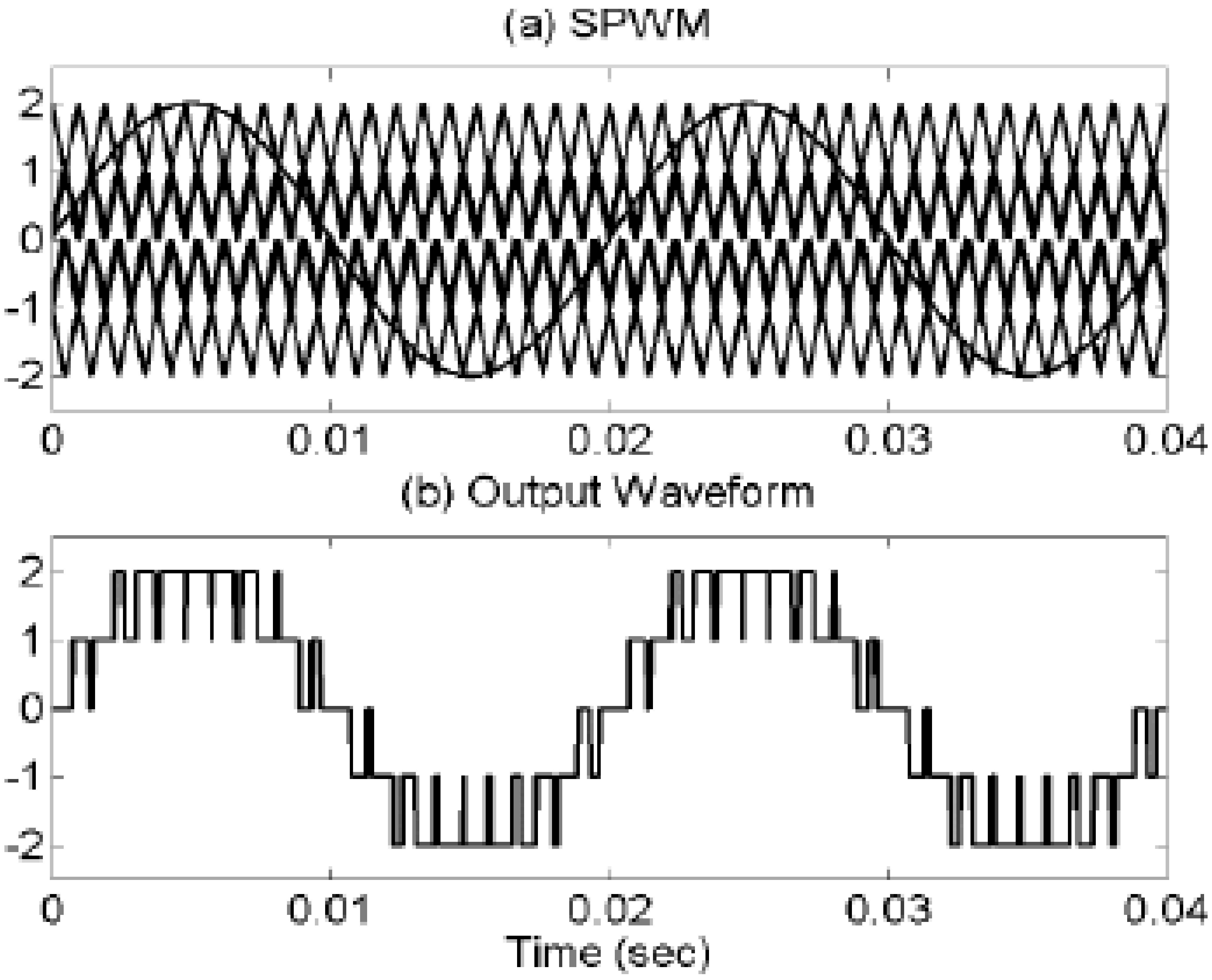


120º operating mode

Sinusoidal Pulse Width Modulation (SPWM)

- The inverter's controller creates a sine wave reference for each phase.
- It compares this sine wave with a high-frequency triangular carrier signal.
- Where the sine wave is higher, the switch is ON; where it's lower, the switch is OFF.
- The result is a series of pulses whose width varies sinusoidally

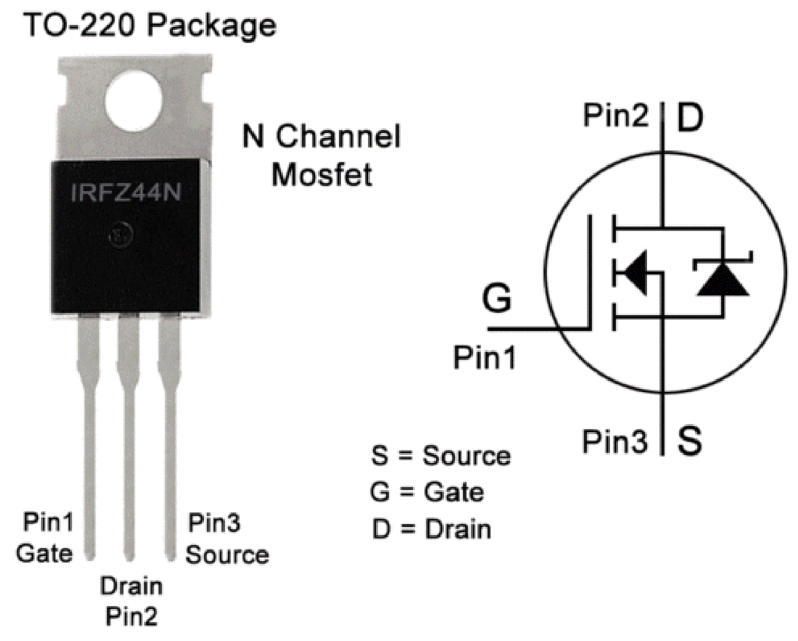



(a) SPWM
2
1
0
-1
-2
0
0.01
0.02
0.03
0.04
(b) Output Waveform
2
1
0
-1
-2
0
0.01
0.02
0.03
0.04
Time (sec)

SWITCHING DEVICES

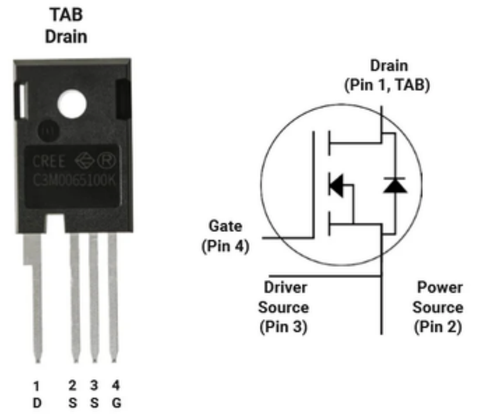
A MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor)

operates as a voltage-controlled device. When a voltage is applied to the gate terminal, it creates an electric field inside the device, allowing current to flow freely between the drain and the source terminals.



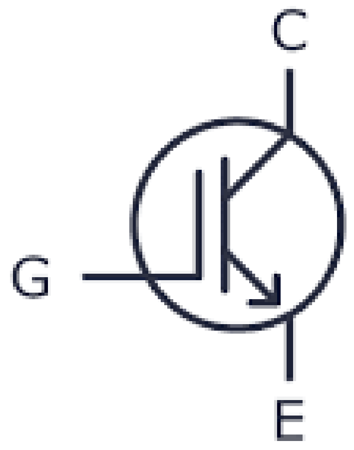
A SiC MOSFET (Silicon Carbide MOSFET)

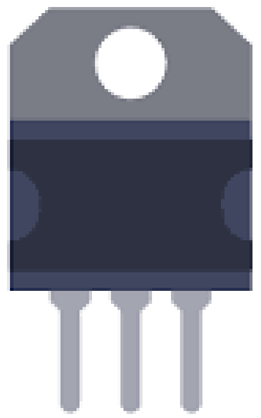
works in the same basic way as a traditional silicon MOSFET — by using a voltage on the gate to control the flow of current between the drain and source — but it is made from silicon carbide instead of pure silicon. This material offers a wider bandgap, allowing SiC devices to operate at much higher voltages, higher temperatures, and faster switching speeds with much lower losses.

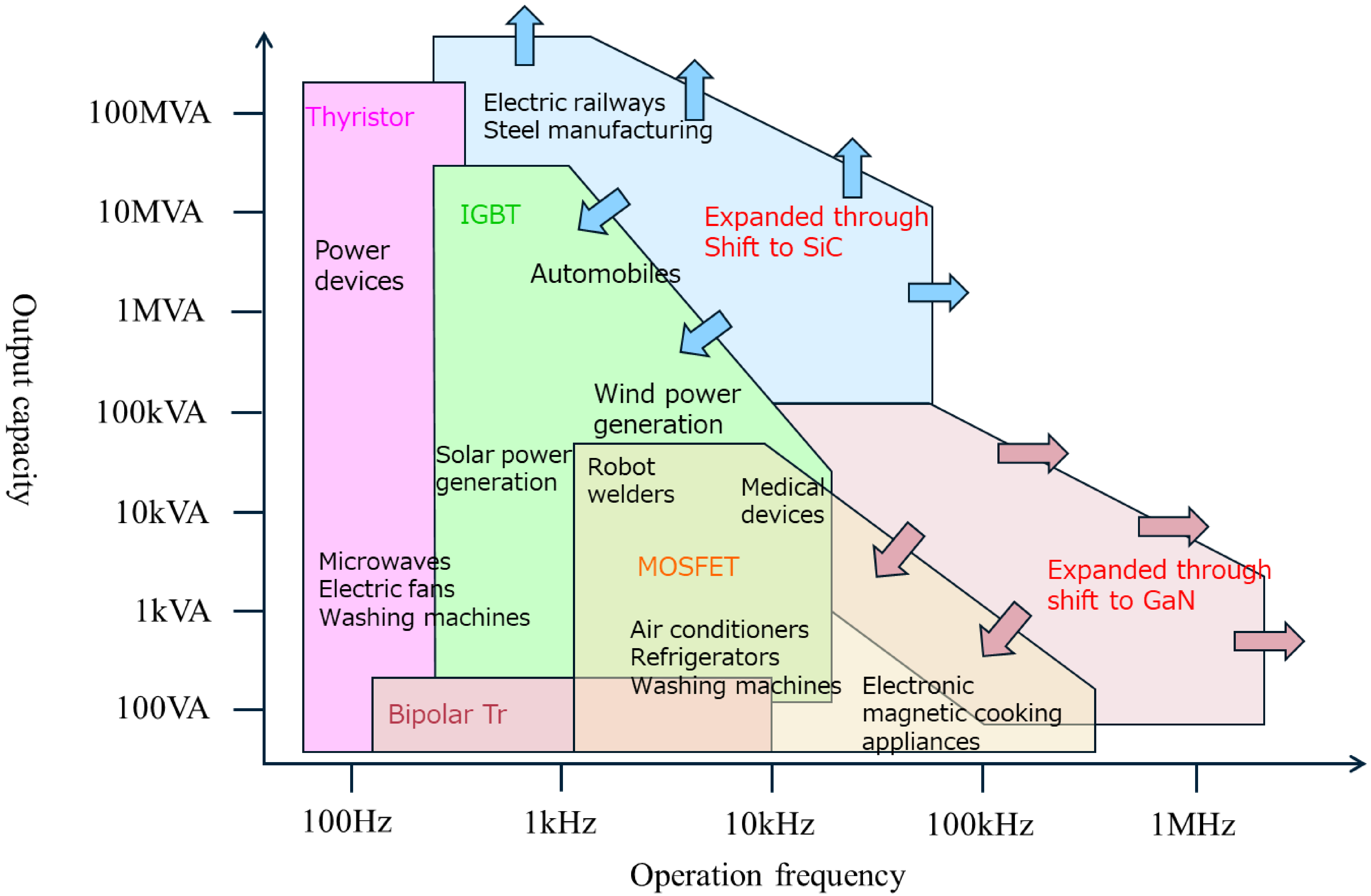


AN IGBT (Insulated Gate Bipolar Transistor)

An IGBT (Insulated Gate Bipolar Transistor) combines the easy gate control of a MOSFET with the high current-handling capability of a bipolar junction transistor (BJT). When a voltage is applied to the gate, it allows a large current to flow from the collector to the emitter.







Output capacity
100MVA
10MVA
1MVA
100kVA
10kVA
1kVA
100VA
100Hz
1kHz
10kHz
100kHz
1MHz
Operation frequency
Thyristor
Power devices
Electric railways
Steel manufacturing
IGBT
Automobiles
Expanded through Shift to SiC
Wind power generation
Solar power generation
Robot welders
Medical devices
MOSFET
Microwaves
Electric fans
Washing machines
Air conditioners
Refrigerators
Washing machines
Electronic magnetic cooking appliances
Bipolar Tr
Expanded through shift to GaN

Component Parameter Calculations

Given Data

- DC Link Voltage, VDC = 600 V
- Load Resistance, R = 10 Ω
- Load Inductance, L = 20 mH
- Output Power, PAC = 5 kW
- Output Frequency, f = 50 Hz
- Modulation Index, Ma = 0.8
- Switching Frequency = 10 kHz

FUNDAMENTAL OUTPUT VOLTAGE (VPHASE,RMS)

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

LOAD IMPEDANCE (Z)

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

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

LOAD CURRENT (I(PHASE,RMS))

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

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

POWER FACTOR (COS Φ)

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

OUTPUT POWER (PAC)

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

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

Component Parameter Calculations

Modified Data

- DC Link Voltage, $V_{DC} = 540\,\mathrm{V}$
- Load Resistance, $R = 10\,\Omega$
- Load Inductance, $L = 20\,\mathrm{mH}$
- Output Power, $P_{AC} = 5\,\mathrm{kW}$
- Output Frequency, $f = 50\,\mathrm{Hz}$
- Modulation Index, $M_a = 0.8$
- Switching Frequency $= 10\,\mathrm{kHz}$

FUNDAMENTAL OUTPUT VOLTAGE (VPHASE,RMS)

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

LOAD IMPEDANCE (Z)

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

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

LOAD CURRENT (I(PHASE,RMS))

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

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

POWER FACTOR (COS Φ)

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

OUTPUT POWER (PAC)

$$P_{AC} = 3 \times V_{phase,rms} \times I_{phase,rms} \times \cos\phi.$$
$$P_{AC} = 3 \times 152.7 \times 12.93 \times 0.847 = 5017\,W.$$

Component Parameter Calculations

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

Calculation of Power Loss for IGBTs

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

IGBT Losses

$$P_{\text{cond}} = V_{CE(\text{sat})} \times I_{\text{avg}} + r_{CE} \times I_{\text{rms}}^2$$

$$P_{\text{sw}} = (E_{\text{on}} + E_{\text{off}}) \times f_{\text{sw}}$$

Diode Losses

$$P_{\text{diode}} = V_F \times I_{\text{avg}} + r_F \times I_{\text{rms}}^2 + E_{rr} \times f_{\text{sw}}$$

Calculation of Power Loss for Mosfets

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

Device C3M0040120K1 (SiC MOSFET)

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

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

- **Switching Loss:**

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

- **Recovery Loss:**

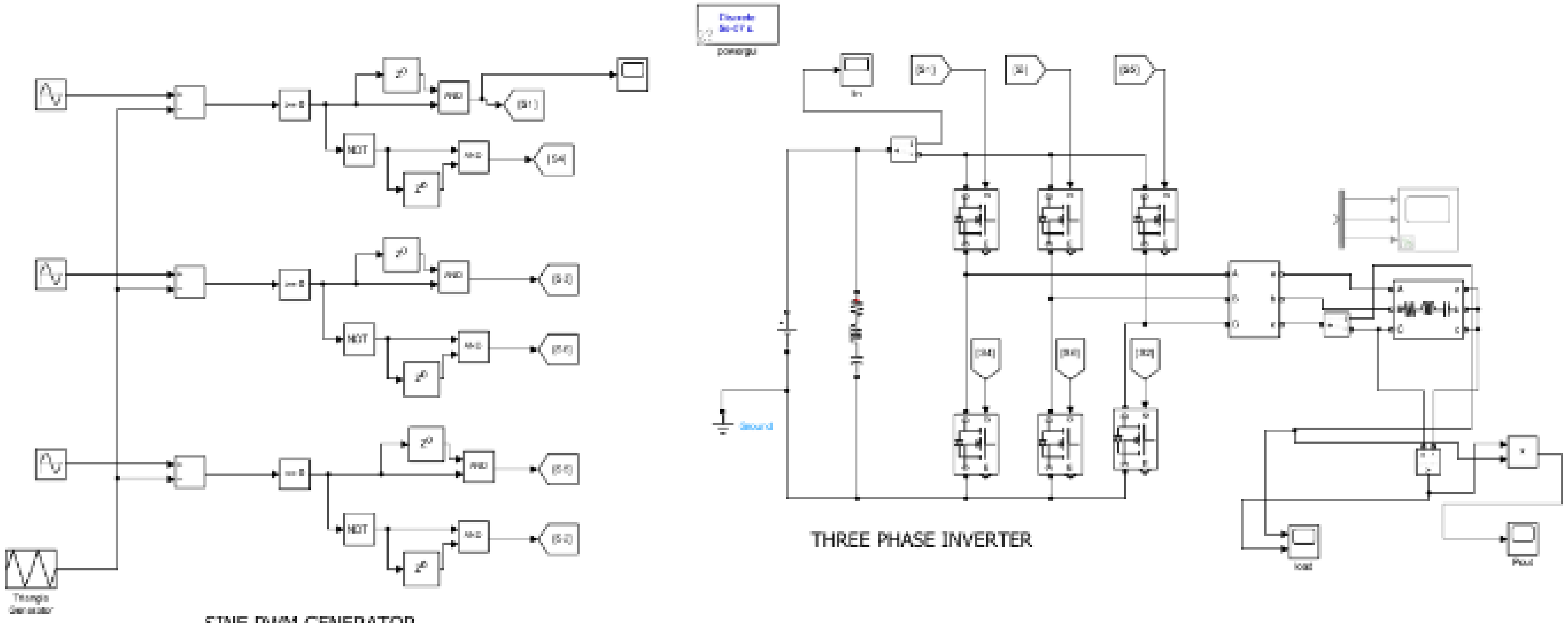
$$P_{rr} = 0.5 \times V_{DC} \times Q_{rr} \times f_{sw}$$
$$P_{rr} = 301.5 \times 10^{-9} \times 540 \times 10^4 = 1.62\text{ W}$$

- **Total Loss:**

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

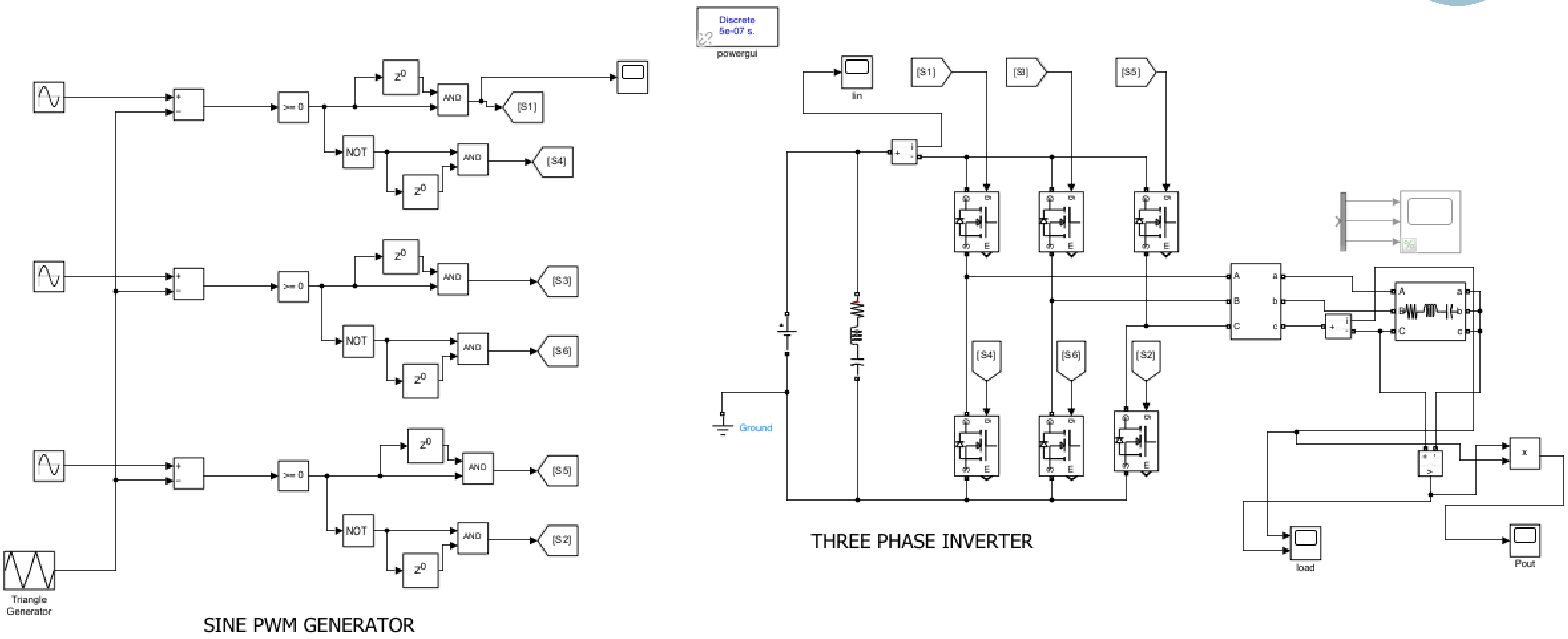
Simulation of 3-Phase Inverter

The 3 phase inverter is build using a Sine 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.



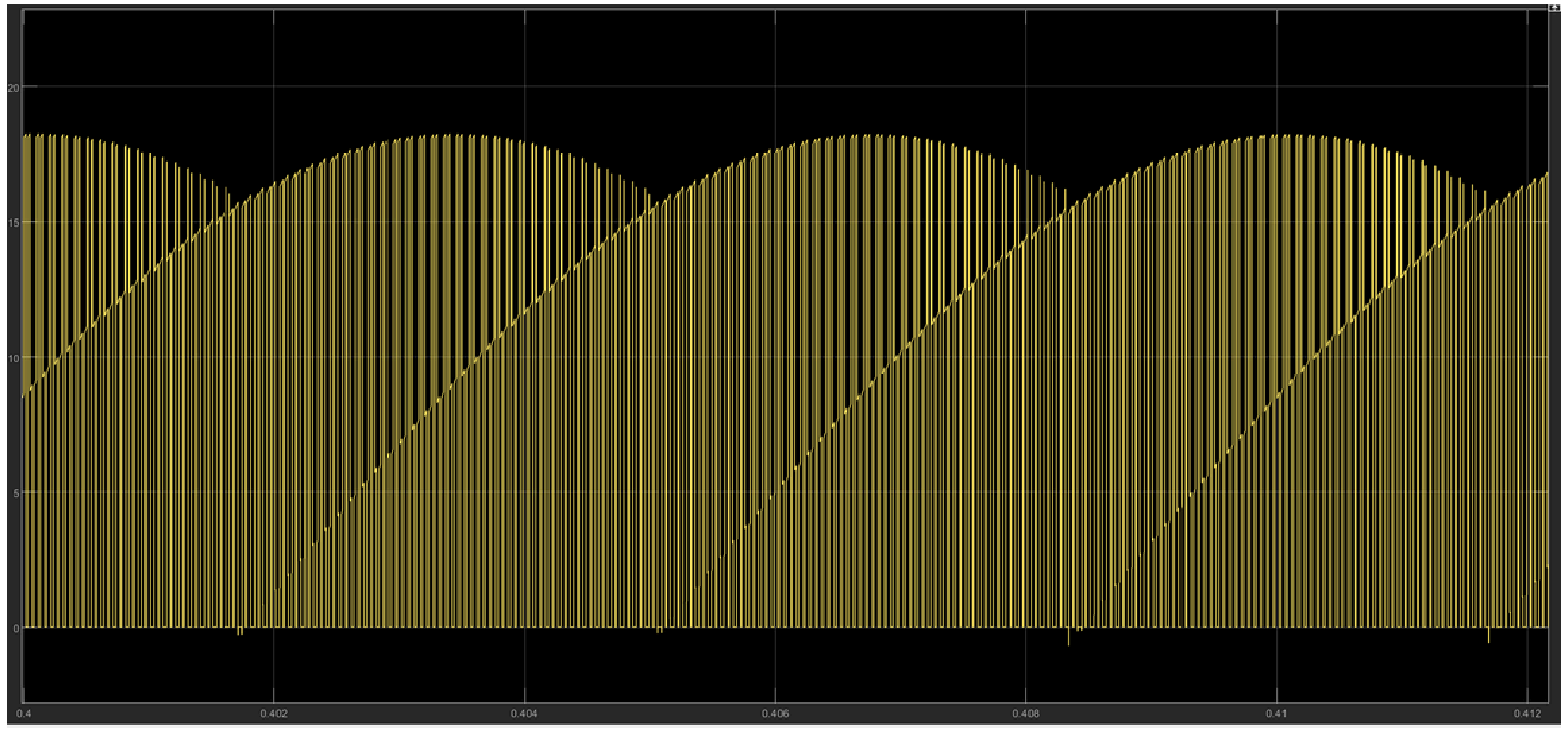
DESIGN OF 3-PHASE INVERTER

DESIGNED IN MATLAB SIMULINK

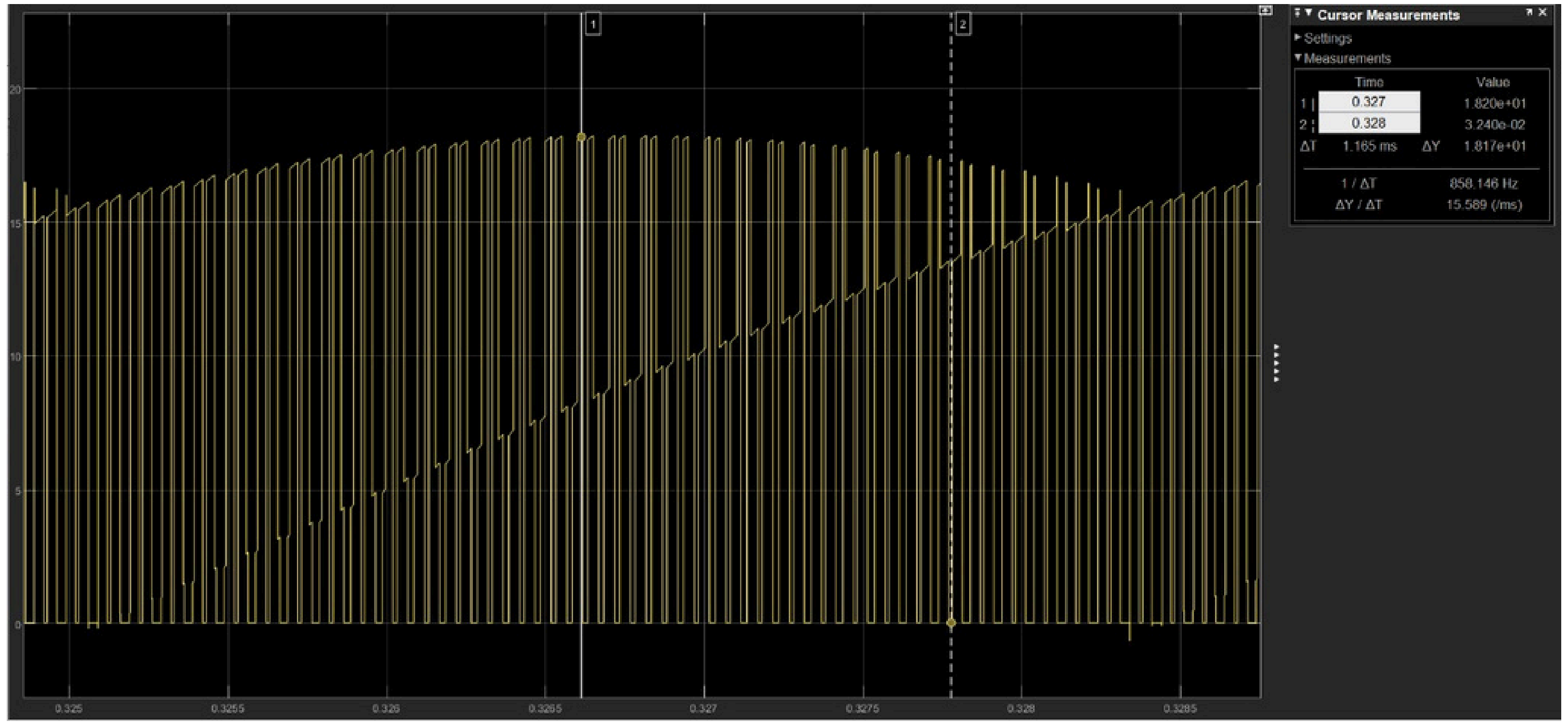


DESIGN OF 3-PHASE INVERTER

Simulations

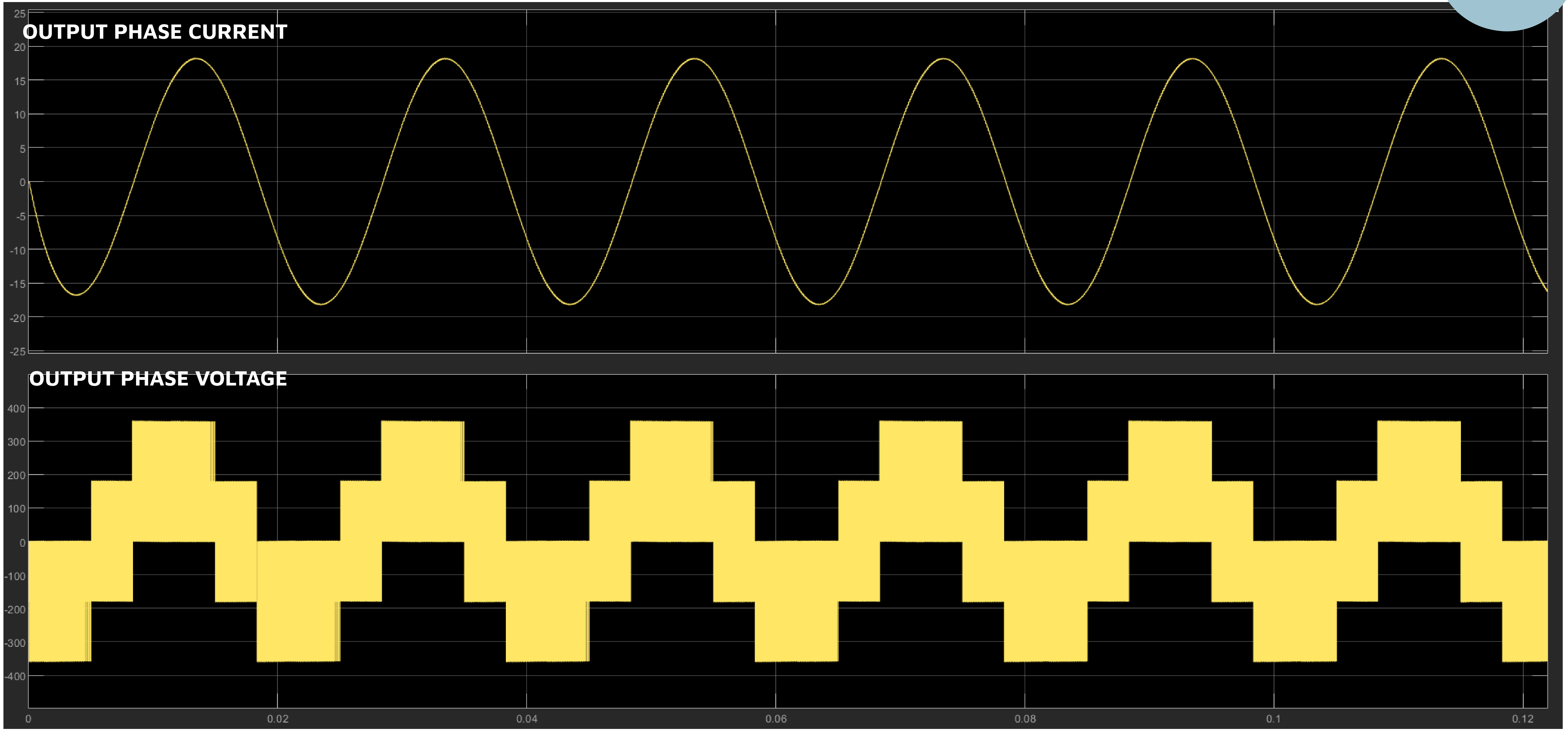


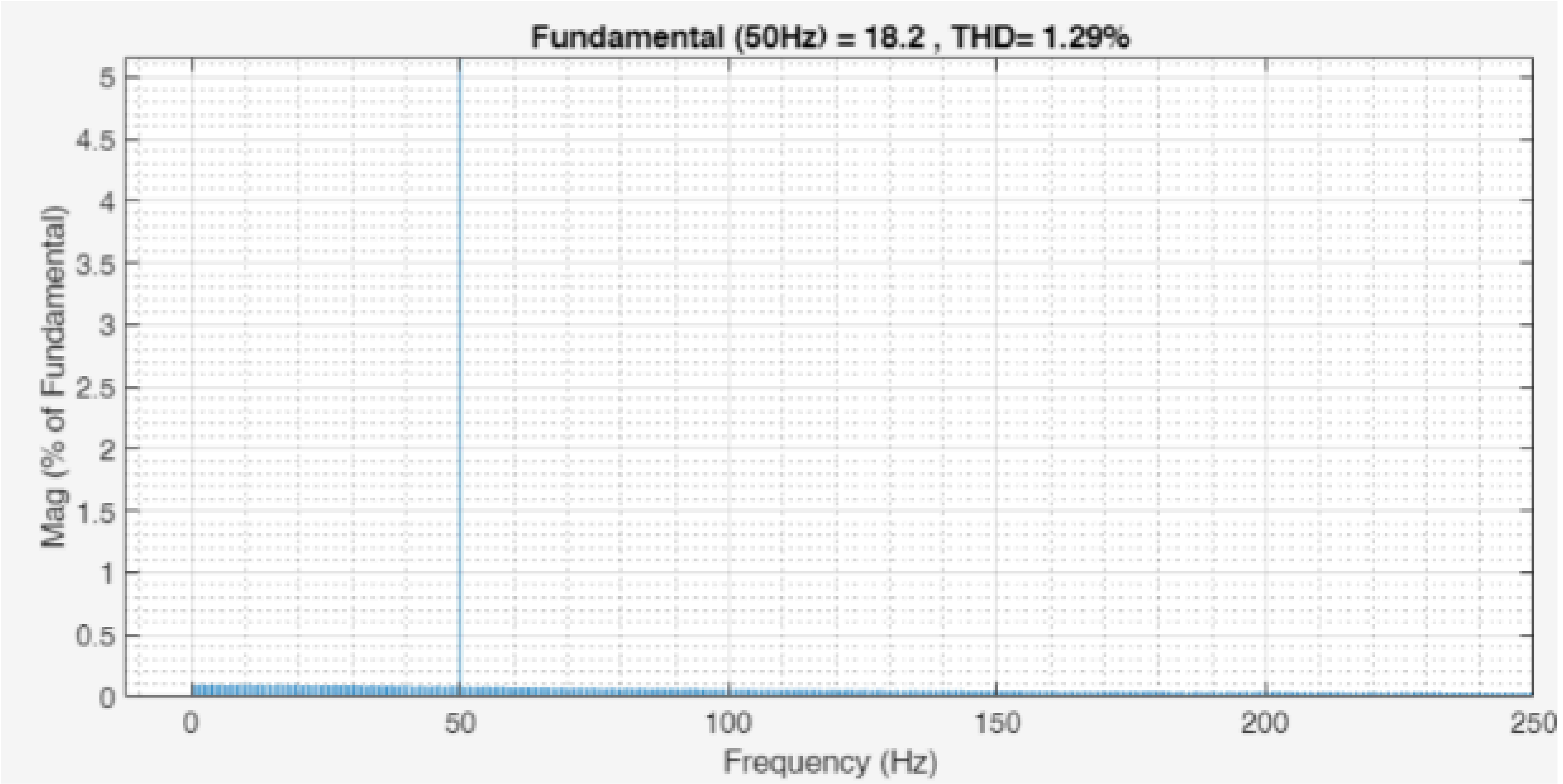
Input current Waveform



Input current Waveform (Magnified)

Simulations - Output Current and Voltage Waveforms





FFT analysis of Output current

Output current amplitude is 18.2A
AND RMS Current is 12.87A

The THD we obtained is quite low, which tells us that the output phase current waveform is almost like a sine-wave

Efficiency Calculations

Efficiency calculated analytically

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 $\frac{P_{out}}{P_{in}} = \frac{5017}{5089.48}$ which is 0.9857 or 98.57 %.

Efficiency Calculations

Efficiency calculated from simulations

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°

FFT analysis of Input current

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°

FFT analysis of Power output

The value of the input current is 9.275 A; therefore, the input power is VDC x Iin or 540 x 9.275 = 5008.6

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

$$P_{in} - P_{out} = 40.5W$$

$$\frac{P_{out}}{P_{in}} = \frac{4968}{5008.5} = 99.19\ \%$$

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 from 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 98.8%, confirming the suitability of the selected MOSFET for this EV application.