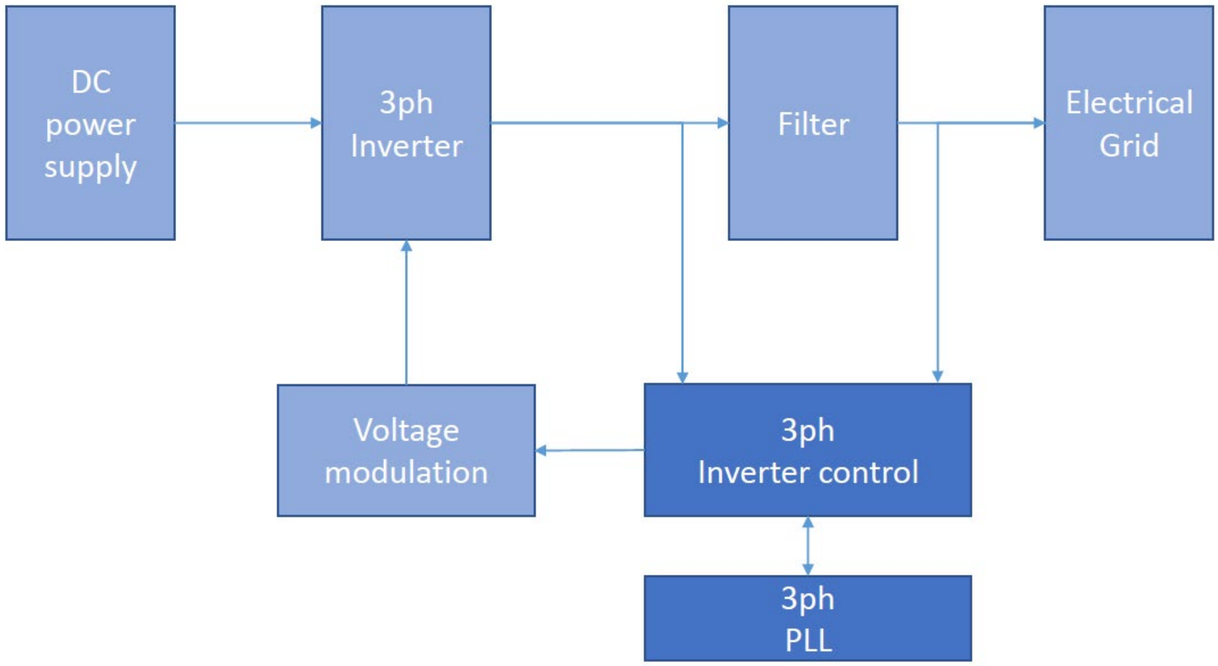

Figure 1. Grid Connected Three Phase Inverter

Model Parameters:

Vdc:

- At t = 0 ms, Vdc = 800 V
- At t = 300 ms, Vdc = 450 V
- At t = 450 ms, Vdc = 900 V

Current setpoint:

- At t = 0 ms, Iac_ref = +200 A
- At t = 150 ms, Iac_ref = -200 A
- At t = 600 ms, Iac_ref = +200 A

Grid:

- V_grid_max = 415 V, phase to phase
- Freq = 50 Hz

Filter:

- Use LCL configuration (500 uH and 100 uF)

Simulation time:

- 800 ms

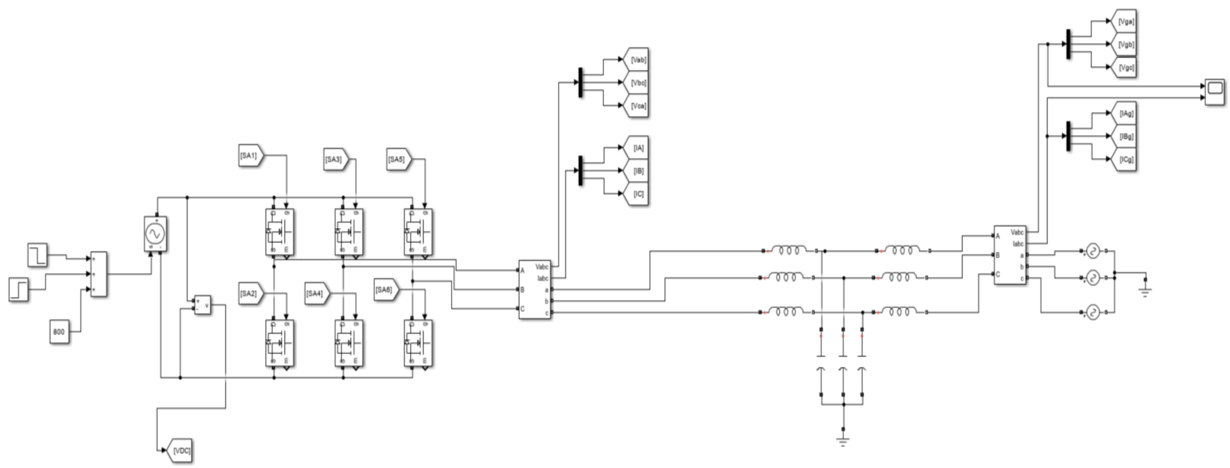

Figure 2. Grid Connected Three Phase Inverter Simulink Model

Alpha-beta transformation or Clarke transformation is a mathematical transformation employed to simplify the analysis of three-phase circuits. It converts a three-phase system into a two-phase orthogonal system. Stationary reference frame (fixed to the stator or stationery in space). This simplifies the analysis and control of three-phase systems, particularly in applications like motor control and power electronics (inverter control, especially in pulse width modulation (PWM) techniques).

$$\begin{aligned} \alpha &= \frac{2}{3}a - \frac{1}{3}b - \frac{1}{3}c, \\ \beta &= \frac{\sqrt{3}}{3}b - \frac{\sqrt{3}}{3}c, \\ 0 &= \frac{1}{3}(a+b+c). \end{aligned}$$

Figure 3. Transformation Equations

$$\begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

Figure 4. Transformation Matrix Form

Park transformation is primarily used in electrical engineering and control theory for analyzing and controlling three-phase electrical systems. It transforms the three-phase currents or voltages into a two-axis (d,q) system. Or Converts a two-phase system (α, β) from Clarke transformation into a rotating reference frame (d,q), which aligns with the rotor or stator magnetic field. This simplifies the analysis and control of AC machines by converting the sinusoidal signals into DC-like quantities under steady-state conditions.

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \\ -\sin(\omega t) & -\sin\left(\omega t - \frac{2\pi}{3}\right) & -\sin\left(\omega t + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

Figure 5. Convert three-phase voltages to d,q,0 rotating frame

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) & 1 \\ \cos\left(\omega t - \frac{2\pi}{3}\right) & -\sin\left(\omega t - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\omega t + \frac{2\pi}{3}\right) & -\sin\left(\omega t + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix}$$

Figure 6. Converts d,q,0 to three-phase voltages

Aspect	Clarke Transformation	Park Transformation
Purpose	Converts three-phase to stationary two-phase.	Converts stationary two-phase to rotating two-phase.
Reference Frame	Stationary (fixed in space).	Rotating (aligned with rotor/stator field).
Output	α, β components.	d, q components (DC-like).
Applications	Simplifies stationary analysis.	Enables motor control (e.g., FOC).
Rotation Angle	No rotation angle involved.	Uses angle θ for transformation.

Figure 7. Clarke VS Park Transformation

A Phase-Locked Loop (PLL) with a Park Transformation is widely used in power electronics and control systems to synchronize the inverter or other equipment with the grid.

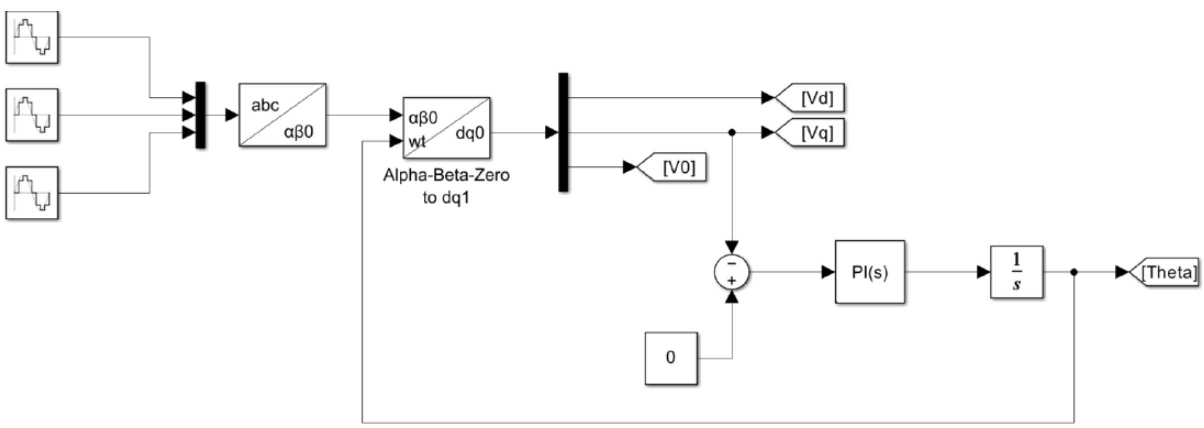

Figure 8. PLL with Park Transformation

1. The input (on the left) is a three-phase signal (grid voltages).
2. Clarke Transformation converts the three-phase (abc) signals into a two-phase orthogonal system in the stationary reference frame (α, β).
3. With Park Transformation (α, β) components are transformed into the rotating $dq0$ frame using the estimated angle θ.
4. The goal of the PLL is to make $v_q = 0$. When $v_q = 0$ the PLL is synchronized with the grid. The v_q signal is subtracted from 0 (reference) to calculate the phase error.
5. A Proportional-Integral (PI) controller processes the phase error to generate the angular frequency ω.
6. The output of the PI controller ω is integrated to compute the phase angle $\theta = \int \omega dt$.

Question 1: Explain what does it mean the sign in the current setpoint.

Answer 1:

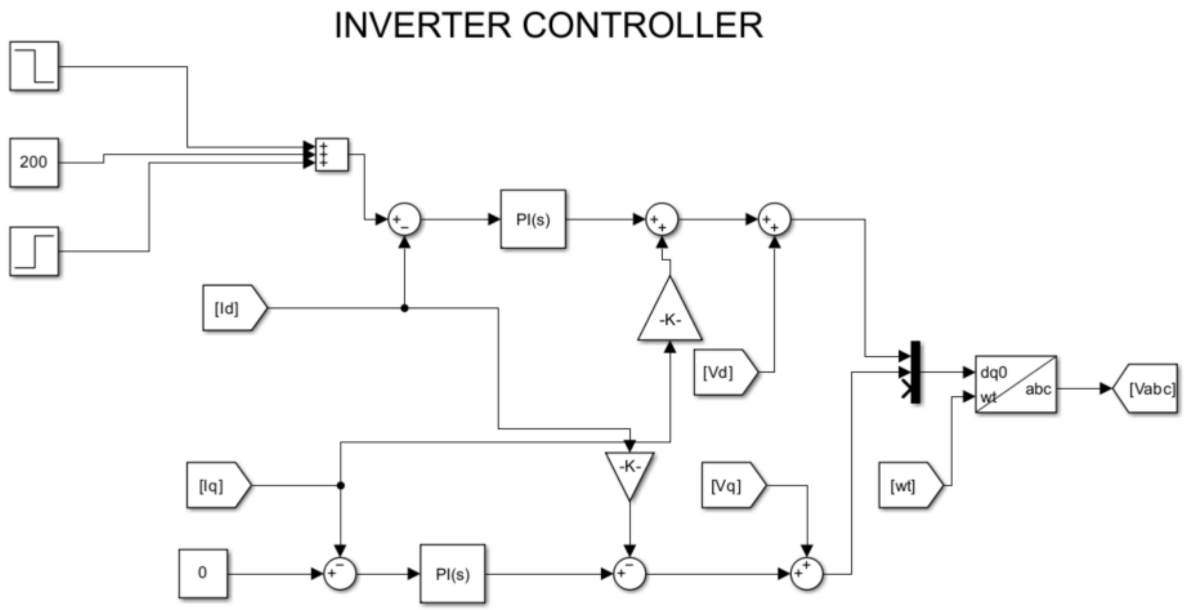

Figure 9. Inverter Controller

In the inverter controller diagram, the sign of I_{ac_ref}, reference AC current, determines the direction of power flow.

1. Positive I_{ac_ref} indicates that the inverter is supplying power to the grid or load. The inverter acts as a source, delivering energy for DC source (Battery) to the AC side.
2. Negative I_{ac_ref} indicates that the inverter is absorbing power from the grid or load. In this case inverter is consuming energy from the AC side, for charging DC battery system.

This sign convention is important in applications such as bidirectional converters for renewable energy systems (PV inverters), and energy storage systems where the inverter may operate in both directions (power supply and absorption).

Question 2: Explain the DC voltage and current levels at each time slot.

Answer 2:

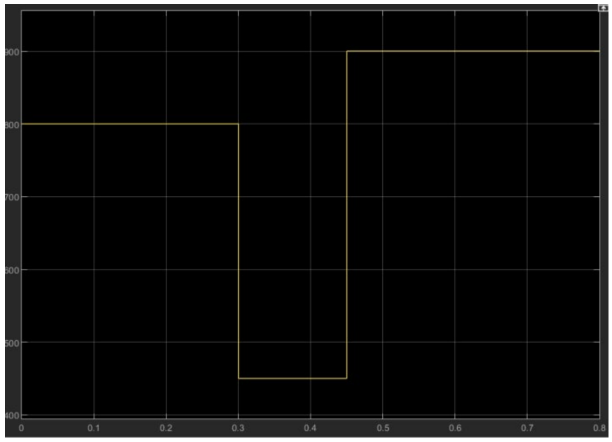

Figure 10. DC voltage for different time slots

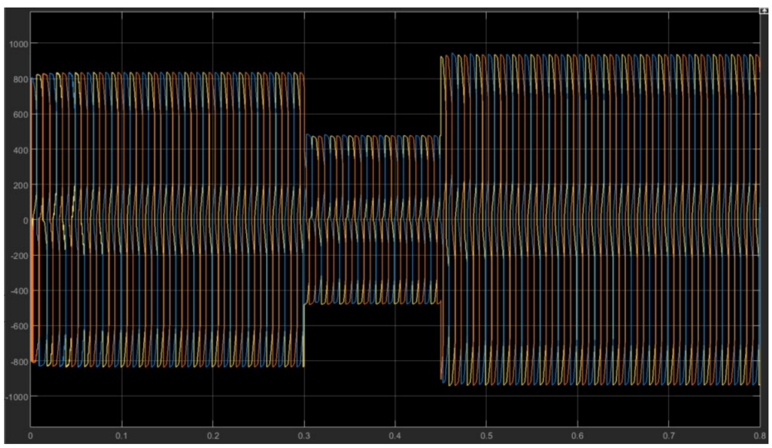

Figure 11. DC Voltage side after inverter

The inverter output voltage (before the filter) directly reflects the changes in DC voltage steps that are imposed on the battery at different time instances. These DC amplitude changes are directly visible in plot as step changes in the inverter output voltage. The inverter output voltage (before the filter) consists of high-frequency PWM switching components imposed on the fundamental sinusoidal waveform. When the DC voltage changes in steps, the PWM duty cycle adjusts to match the new DC level, but the switching ripple remains, that’s why fundamental sinusoidal waveform changes amplitude, but ripple remains.

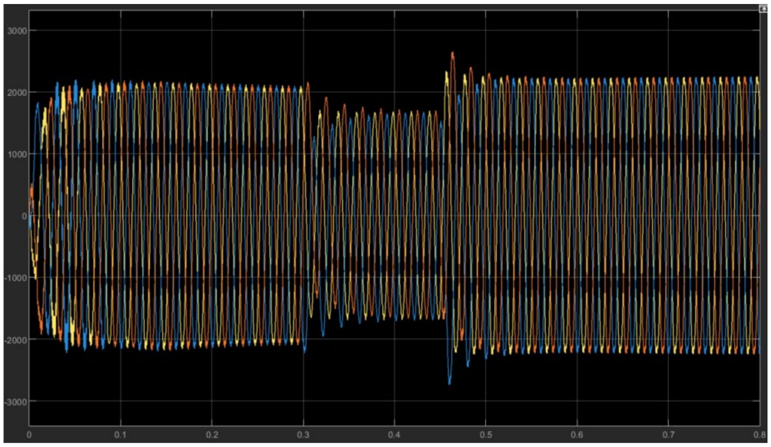

Figure 12. DC side current

Question 3: Explain the AC voltage and current levels at each time slot

Answer 3:

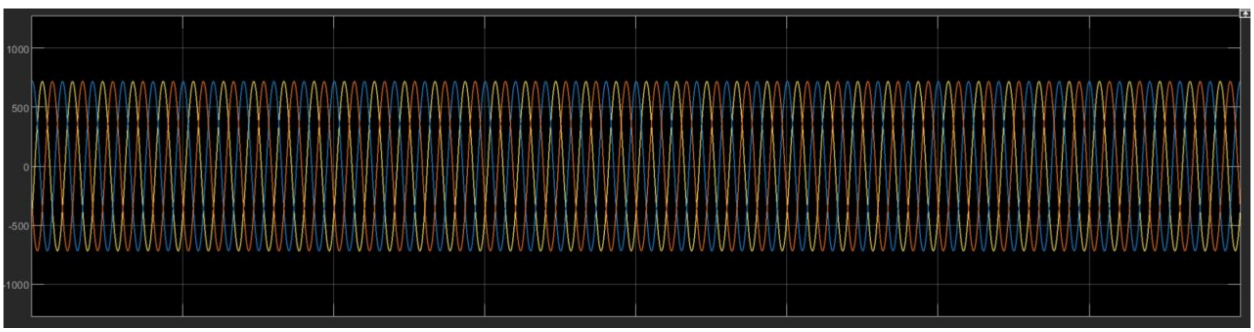

Figure 13. AC side voltage

The grid voltage appears as a clean sinusoidal waveform because of the filter placed between the inverter and the grid. This filter smooths out the high-frequency PWM components, leaving only the fundamental sinusoidal voltage to be injected into the grid. Before the filter the voltage waveform is distorted and contains high-frequency switching components. After the filter (grid voltage) the high-frequency ripple is removed, and the waveform appears sinusoidal.

Also, the grid itself enforces a clean sinusoidal voltage because it is a large system with very low impedance, "overpowering" any disturbances introduced by inverter.

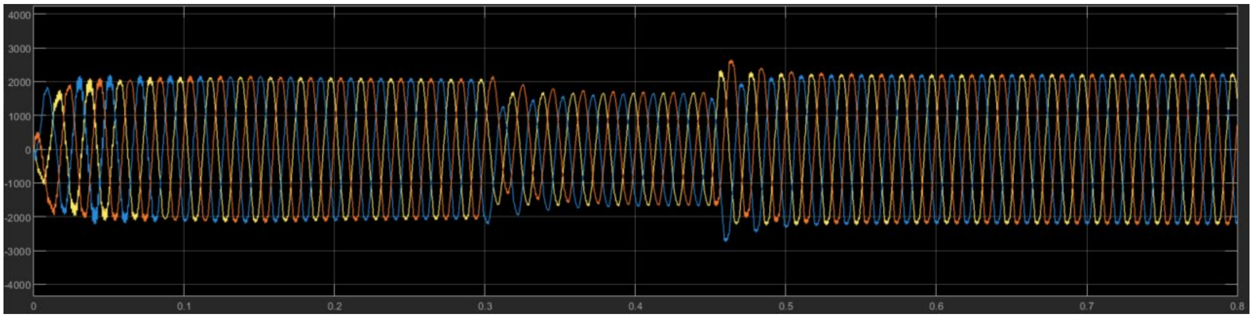

Figure 14. AC side current

The AC current on the grid side is following the waveform of voltage before the filter after the inverter (distorted inverted output). The grid current depends on the voltage difference between the inverter output and the grid voltage, as well as the impedance of the circuit:

$$I_{grid} = \frac{V_{inverter} - V_{grid}}{Z_{filter} + Z_{grid}}$$

Because inverter output voltage $V_{inverter}$ contains high-frequency components (due to PWM switching ripple) and step changes (due to battery voltage variations we impose in time steps), these components are influencing the current.

Question 4: Which is the system efficiency in each time slot

Answer 4:

The efficiency of the inverter can be defined as:

$$\eta = \frac{P_{output}}{P_{input}} \cdot 100\%$$

When the power flow is from battery to the grid:

P_{output} – the power delivered to the grid (AC side)

P_{input} – power drawn from the battery (DC side)

We have 3 times slots with step changes in DC voltage. The voltage after the inverter (before the filter) contains high-frequency components and step changes. The grid voltage is clean and sinusoidal.

$P_{input} = V_{dc} \cdot I_{dc}$

$P_{output} = V_{rms} \cdot I_{rms} \cdot PF$