ABSTRACT

This study seeks to examine the complexity of Voltage-Oriented Control (VOC) coupled with a decoupling controller for grid-tied inverters. Through extensive study and analysis, we want to understand the fundamental concepts behind VOC and its use in improving the performance of grid-tied inverters. This study also includes the design and implementation of a sinusoidal pulse width modulation technique suited exclusively for grid-tied inverters, which ensures efficient and dependable operation. Furthermore, we investigate the dynamics of active and reactive power regulation in grid-tied inverters in order to explain techniques for efficient power management and grid integration. By attaining these goals, this study helps to further our understanding and practical use of grid-tied inverter systems in current power networks.

I. INTRODUCTION

Grid-tied inverters are critical components of contemporary power networks, transforming direct current (DC) from renewable energy sources such as solar panels into alternating current (AC) that may be sent into the grid. Maximizing the efficiency and dependability of these inverters is critical to ensuring the seamless integration of renewable energy into the current grid infrastructure. Voltage-Oriented Control (VOC) using a decoupling controller is a potential method for improving the performance of grid-tied inverters by providing more flexibility and control over their operation. In this project, we investigate the theory and application of VOC using a decoupling controller for grid-tied inverters. Our goal is to obtain a thorough grasp of how this control method works and its potential benefits for enhancing the performance of grid-tied inverters. In addition, we want to develop a sinusoidal pulse width modulation system optimized exclusively for grid-tied inverters, allowing for exact control over the produced AC output. Furthermore, we intend to investigate the dynamics of active and reactive power regulation in the setting of grid-tied inverters. By investigating these characteristics, we want to gain insights into improving power management and establishing seamless grid integration, so increasing the overall efficiency and dependability of renewable energy systems. This project aims to enhance grid-tied inverter technology, opening the door for a more sustainable and resilient energy future.

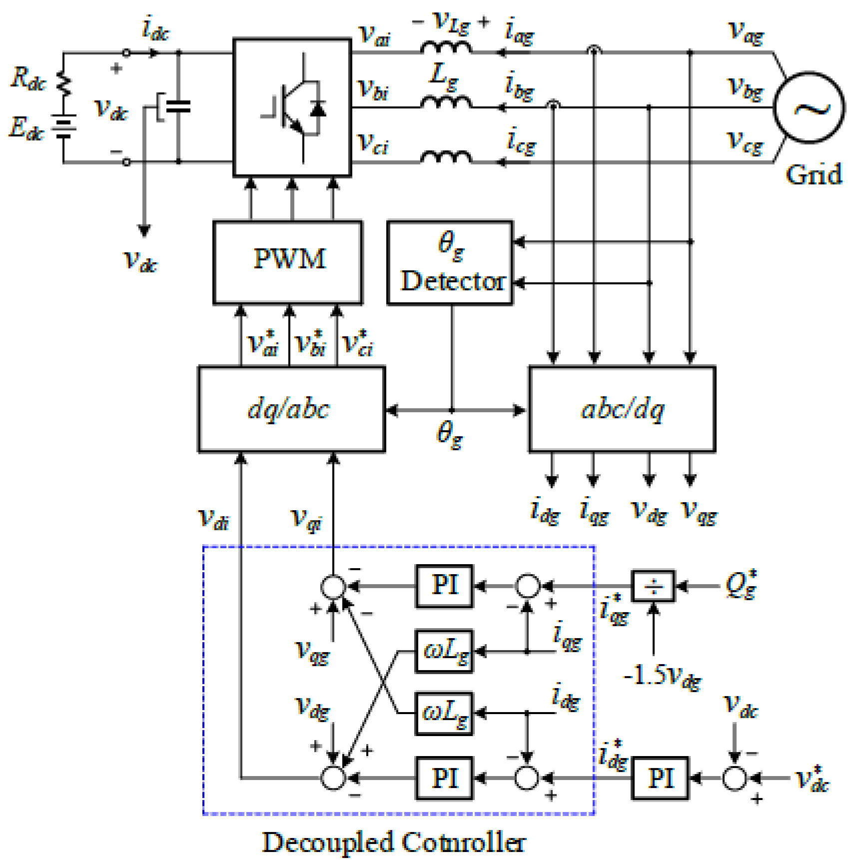

Fig. 1[1] Block Diagram of Grid-Tied Inverter with Decoupled Voltage Oriented Controller

In this block diagram, we observe the control of a Grid-Tied Inverter through a Voltage-Oriented Controller (VOC). The advantages of using VOC include ensuring grid stability, maintaining power quality, achieving efficient power conversion, and controlling reactive power. Fundamentally, VOC operates on the transformation between the abc stationary reference frame and the dq synchronous reference frame, where the DC component variables remain steady. To understand the three-phase system's behavior, we need to track the grid voltages and pinpoint a specific angle (θg) that reflects the voltage orientation. This angle is essential for translating between two different ways of representing the system (dq/abc and abc/dq). Angle θg detection can be accomplished through either digital filters or phase-locked loops (PLLs). The system comprises three feedback current loops: two inner loops for dq axis currents (i_{dg} & i_{qg}) and one outer loop for DC voltage feedback (vdc)[2]. These feedback loops facilitate the calculation of discrepancies between reference and actual values. By utilizing these discrepancies, v_{di}

and v_{qi} are computed, which are then employed for the dq/abc transformation to generate Pulse Width Modulation (PWM) signals for the grid-tied inverter[2].

The rationale behind employing a decoupled controller lies in the interrelation between the derivative of the d-axis line current (i_{dg}) and both d and q axis currents (i_{qg})[2]. This interdependence indicates cross-coupling in the system's control, potentially leading to challenges in controller design and suboptimal dynamic performance[2]. To address this issue effectively, a decoupled controller is employed.

II. SIMULATION DATA AND RESULTS

As part of our project, we are tasked with implementing Grid Tied Inverter with Decoupled Voltage Oriented Controller. To achieve this, we have been provided with parameters to develop the model using MATLAB R2023b. The parameters are mentioned in Table 1[1].

TABLE 1. Parameters for Grid Tied Inverter with Decoupled VOC

Parameter	Symbol
Rated inverter output apparent power	2.00 MVA
Grid filter parameters	1.19025 mΩ (0.005pu) and 0.12629 mH (0.2 pu)
Battery voltage	1259 V
Reference DC voltage	1220 V
DC-link capacitor	44571.853 µF (4.0pu)
DC-link resistor	30 mΩ
Switching frequency (F_{swg})	2040 Hz (34 times f_g)
Sampling frequency (F_{sampg})	10000 Hz
Switching devices	Universal bridge with IGBT/diodes
Grid line-line rms voltage, v_g	690 V (rms)
Grid frequency, f_g	60 Hz
Active power delivered to the grid	1.6 MW
Reactive power delivered to the grid	Refer to the project requirements

As per these parameters, I designed the Grid Tied Inverter using Voltage Oriented Controller in MATLAB R2023b [1]. The model is shown in Fig. 1.

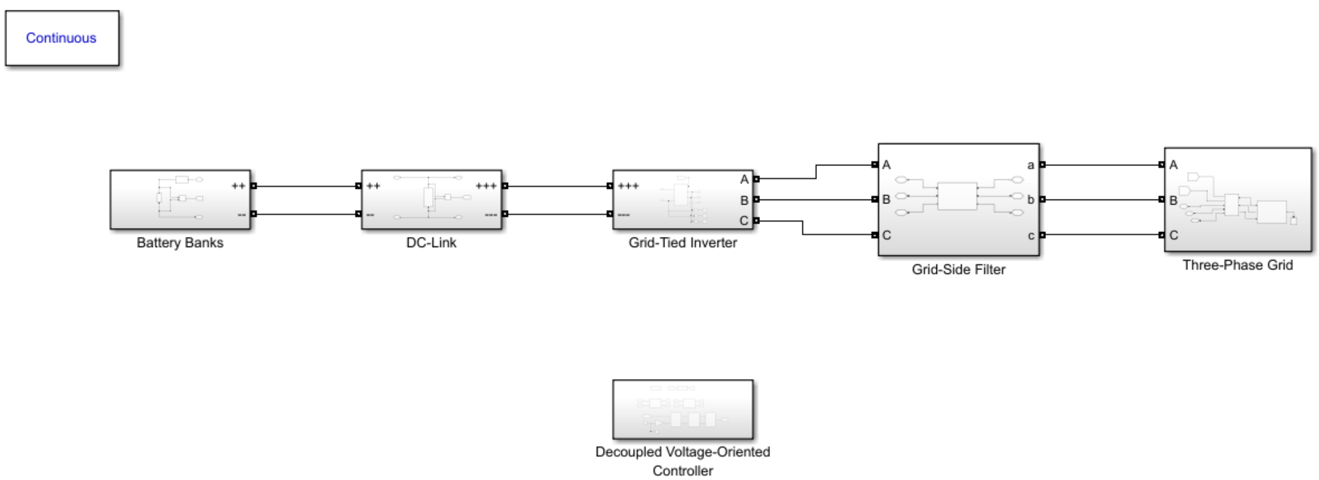

Fig. 2 Simulink Model of Grid Tied Inverter using Decoupled Voltage Oriented Controller

To simplify the model and make it easier to analyze, we're using battery banks instead of generators. These batteries work with a special converter at the beginning (front-end converter) to provide power. There's also a DC-link component that controls how much active power gets sent to the grid. The grid-tied inverter establishes a connection with the grid via an RL filter, with control entrusted to a decoupled voltage-oriented controller. This setup comprises several subsystems, each serving a distinct purpose. Initially, the grid angle (θg) is determined by measuring grid voltages, a crucial step for abc/dq and dq/abc transformations. The PLL subsystem is instrumental in this process, facilitating the measurement of grid angle (θg) by converting three-phase grid voltages into Vα and Vβ components[3].

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -{}^{1}/_{2} & -{}^{1}/_{2} \\ 0 & {}^{\sqrt{3}}/_{2} & -{}^{\sqrt{3}}/_{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_C \end{bmatrix}$$

In the above equation, v_a, v_b, v_C are phase voltages, v_α and v_β are αβ voltages.

By using v_α and v_β, the grid angle θ_g can be calculated as[3]:

$$\theta_g = tan^{-1}(\frac{v_\beta}{v_\alpha})$$

We can use the dq/abc transformation to take the voltages of the power grid, which are constant (stationary), and convert them into rotating (synchronous) dq voltages. This conversion is achieved through the following equation[3]:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos(\theta - \frac{4\pi}{3}) \\ -sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin(\theta - \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

In the above equation, v_a, v_b, v_C are grid phase voltages, v_d and v_q are dq grid voltages, and the grid angle θ_g. We have used above equation to calculate the dq grid voltages which can be utilized to obtain phase grid currents and dq grid currents.

The system adjusts the DC voltage (v_{dc}) to control how much power goes into the grid. It uses a reference value (v_{dc_ref}) and a target for reactive power (Q_{g_ref}) to figure out the ideal current (dq reference grid currents) to inject. Then, another controller uses these dq currents to calculate the voltages needed inside the inverter (inverter-side dq voltages). Finally, this conversion (dq/abc transformation, see the equation below[3]) turns internal info and the grid angle into the regular three-phase (abc) voltages that the inverter outputs.

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta - \frac{4\pi}{3}\right) & -\sin(\theta - \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

To analyze how the system behaves under different conditions, we use the Q_{g_ref} block (explained in Figure 2) to control the amount of reactive power delivered at different times. By setting specific values in the Q_{g_ref} block (like those shown in the figure), we can simulate three different steady-state scenarios for our analysis.

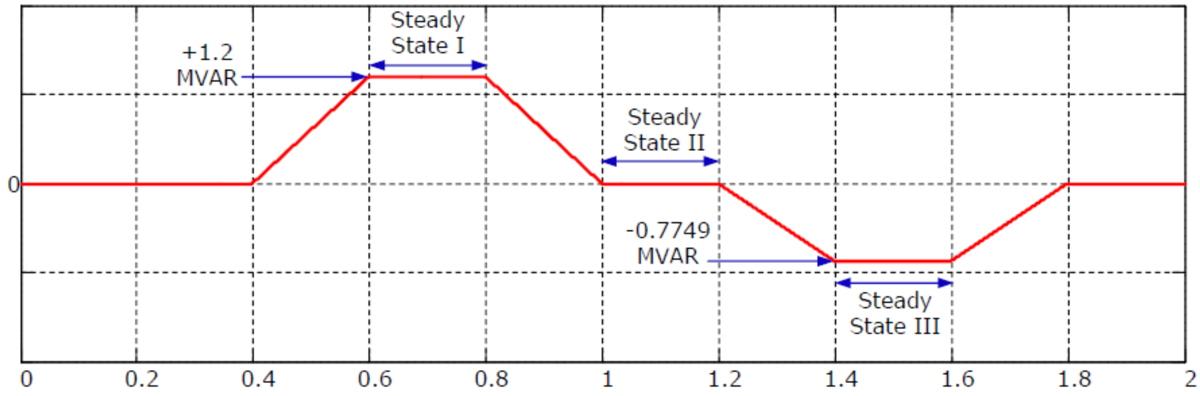

Fig. 3 [1] Q_{g_ref} Block Parameters

The inverter's gate signals are generated using Sinusoidal Pulse Width Modulation (SPWM), which leverages comparisons between the inverter-side DC voltage and a high-frequency carrier signal. This comparison process within SPWM dictates the switching behavior of the inverter to synthesize the desired gating signals[1].

$$V_{cr} \leq V_a^* \rightarrow V_{g1} = 1, V_{g2} = 0$$

$$V_{cr} \leq V_b^* \rightarrow V_{g3} = 1, V_{g4} = 0$$

$$V_{cr} \leq V_c^* \rightarrow V_{g5} = 1, V_{g6} = 0$$

An internal block specifically calculates a value called the modulation index. This calculation relies on the following equation[1]:

$$m_a = v_{m,rms} \times \sqrt{2}$$

This model allows us to generate the different voltage and current waveforms specified in the project. We can then analyze these waveforms under stable operating conditions (steady state analysis). Additionally, a mathematical tool called Fast Fourier Transform (FFT) will be used to examine the grid current in each of these stable scenarios.

A. Simulation Results

Task-1: Decoupled VOC Transient Analysis

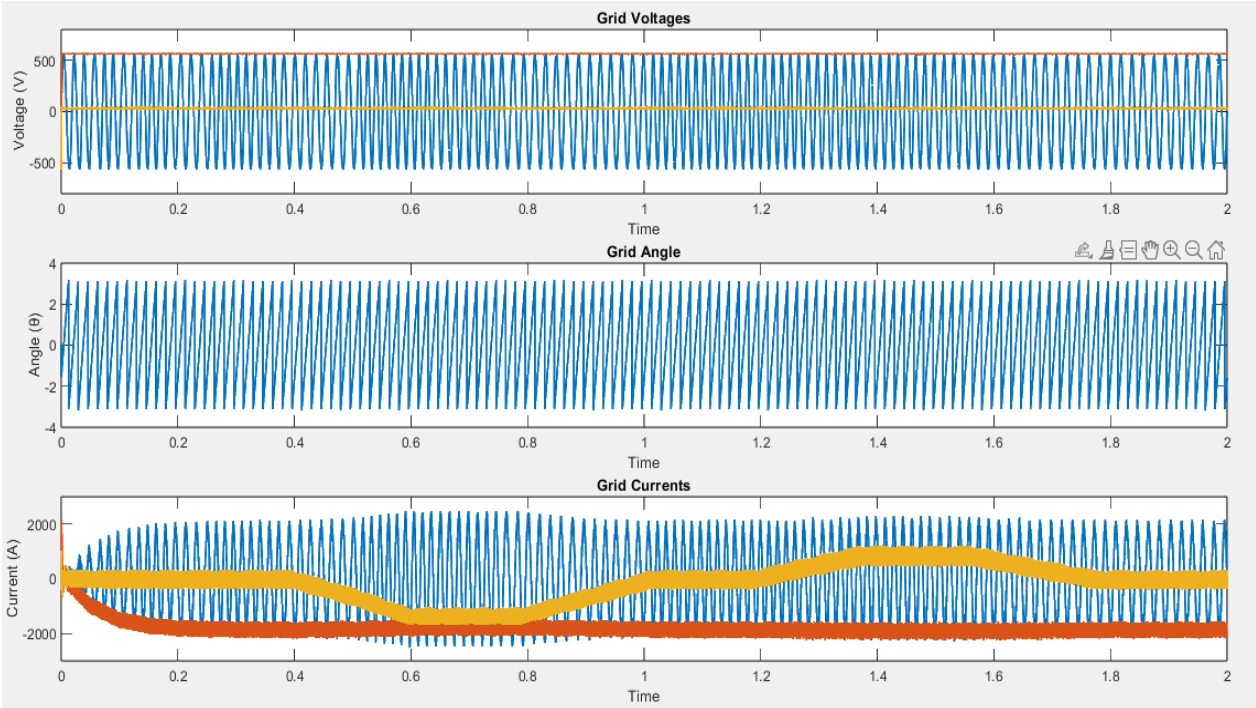

Fig. 4 Grid Voltage (V_{ag}, V_{dg}, V_{qg}), Grid Angle (θ_g) and Grid Currents (I_{ag}, I_{dg}, I_{qg})

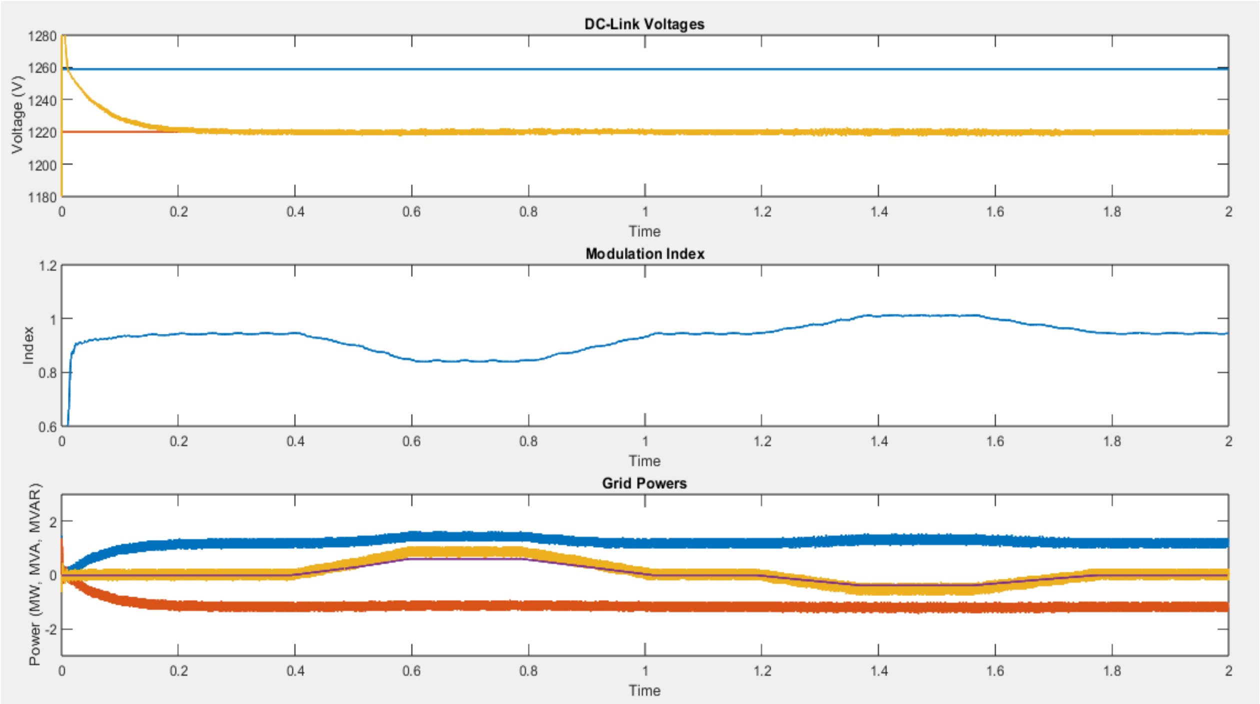

Fig. 5 DC-Link Voltage ($V_{battery}$, V_{dc}, V_{dc_ref}), Modulation Index (m_a) and Grid Powers (S_g, P_g, Q_g, Q_{g_ref})

Explanation:

In fig. 4 waveform-1, V_{ag} is calculated as follows:

Given, grid line to line rms voltage is 690V. So, for sinusoidal waveform (AC Nature), the peak value will be,

$$v_{ag} = \left(\frac{690}{\sqrt{3}}\right) \times \sqrt{2} = 562.36$$

For v_{dg} and v_{qg}, we convert the grid voltage to dq synchronous frame using abc/dq transformation. In the VOC scheme, when the synchronous frame's d-axis aligns with the grid voltage, the d-axis voltage (v_{dg}) simply matches the grid voltage's magnitude. This perfect alignment forces the q-axis voltage (v_{qg}) to zero, as the VOC scheme prioritizes controlling active power through v_{qg} and minimizes reactive power (related to v_{qg}).

In fig. 4 waveform-2, we know that v_g is continuously fluctuating by grid frequency. So, its magnitude changes along with its angle (θ_g). When v_g reaches its negative peak, θ_g will be zero. As v_g rotates, θ_g increases. After a full cycle (2π), v_g hits its negative peak again, and θ_g returns to zero or value close to it.

In fig. 4 waveform-3, we know that i_{ag} (peak value) can calculated as:

$$i_{ag} = \frac{P_{base}}{v_{rms}} \times \frac{\sqrt{2}}{\sqrt{3}} = \frac{2 \times 10^6}{690} \times \frac{\sqrt{2}}{\sqrt{3}} = 2369.1044$$

As the voltage is in sinusoidal form then, we will have current of sinusoidal nature. We can calculate the i_{dg} using abc/dq transformation. The values of i_{ag} and i_{dg} remains constant during the simulation. While the value of i_{qg} varies with the value of reactive power. It can be given by[1]:

$$i_{qg} = \frac{Q_g}{-1 \cdot 5 \times v_g}$$

Here, Q_g indicates the reactive power, which can be considered as zero for unity power factor operation, as negative value for leading power factor operation and positive value for lagging power factor operation. Considering this scenario, we can say that i_{qg} is negative in between 0.6 to 0.8 sec which indicates that reactive power is positive (which can be seen in fig. 5 waveform-3) and i_{qg} is positive in between 1.4 to 1.6 which shows that reactive power is negative (which can be seen in fig. 5 waveform-3).

In fig. 5 waveform-1, we can see that $V_{battery}$ and V_{dc_ref} remains constant throughout the simulation while we can see a sudden rise during the start operation in the value of V_{dc}. This happens due to capacitor that is present in the dc-link sub-system. After that it balances the value and reaches in level of $V_{battery}$.

In fig. 5 waveform-2, the value of modulation index is calculated by taking V_a as signal. When the inverter operates under normal conditions, this modulation index typically sits around 0.8[2]. By manipulating the modulation index, the inverter can adjust its internal DC reference voltage. This adjustment in DC voltage, which can vary by about 20%, allows for fine-tuning the voltage supplied to the grid[2].

In fig. 5 waveform-3, the S_g, P_g , and Q_{g_ref} remains constant throughout the operations while the value of Q_g changes in respect to i_{qg}.

Task-2: Decoupled VOC Steady-State Analysis

Steady State-1

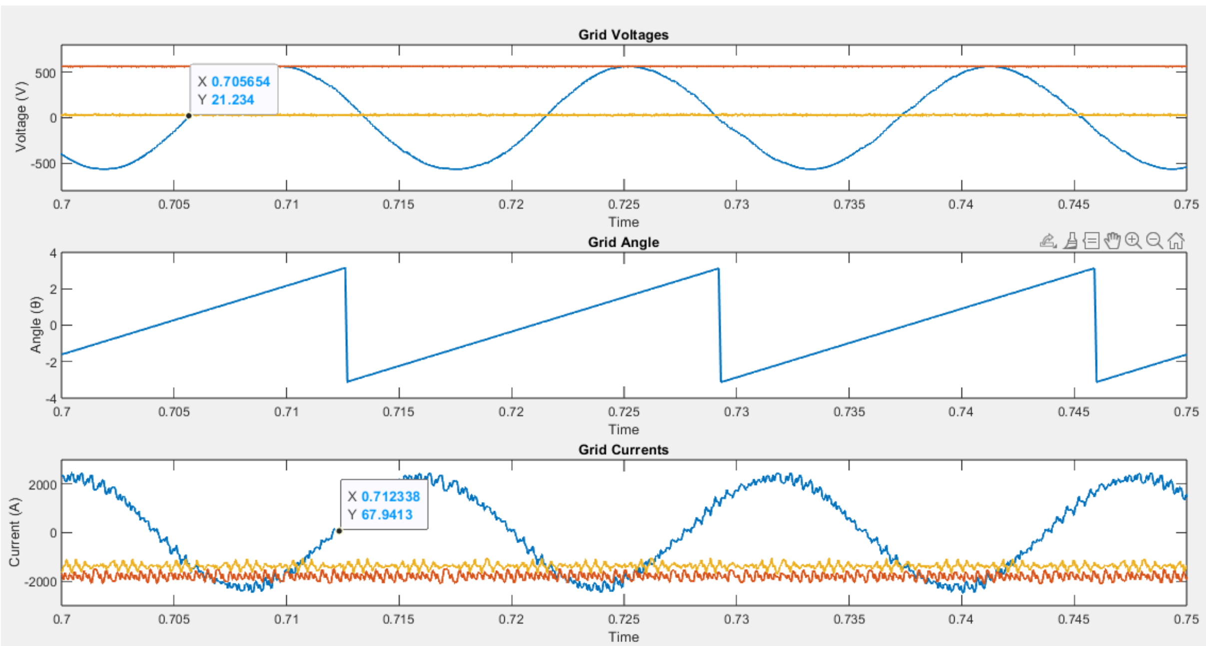

Fig. 6 Steady State -1 Grid Voltage (V_{ag}, V_{dg}, V_{qg}), Grid Angle (θ_g) and Grid Currents (I_{ag}, I_{dg}, I_{qg})

Explanation:

In fig 6. waveform, we can see that the values i_{ag} is lagging behind from v_{ag}. So, we can get the power factor as follows:

$$\theta = (0.7123 - 0.7056) \times 360 \times 60 = 144.72 \; or - 35.28$$

As the value of reactive power is positive (Q_g = + 1.2 MVAR) and power factor angle is between 90 and 180. Using the phase diagram given in project instruction, we can see that the power factor angle is in third quadrant with lagging power factor.

Steady State-2

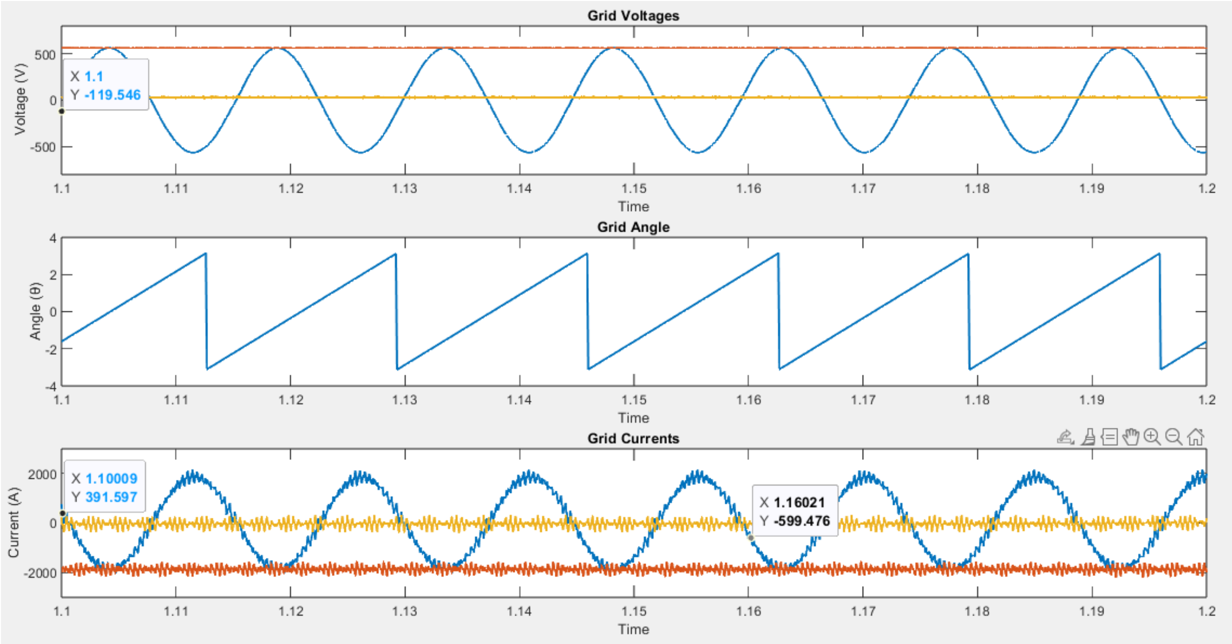

Fig. 7 Steady State -2 Grid Voltage (V_{ag}, V_{dg}, V_{qg}), Grid Angle (θ_g) and Grid Currents (I_{ag}, I_{dg}, I_{qg})

Explanation:

In fig 7. waveform, we can see that the values i_{ag} is neither lagging nor leading from v_{ag}. So, we can get the power factor as follows:

$$\theta = (1.1 - 1.1) \times 360 \times 60 = 0$$

As the value of reactive power is zero (Q_g = 0 MVAR) and power factor angle is zero.

Steady State-3

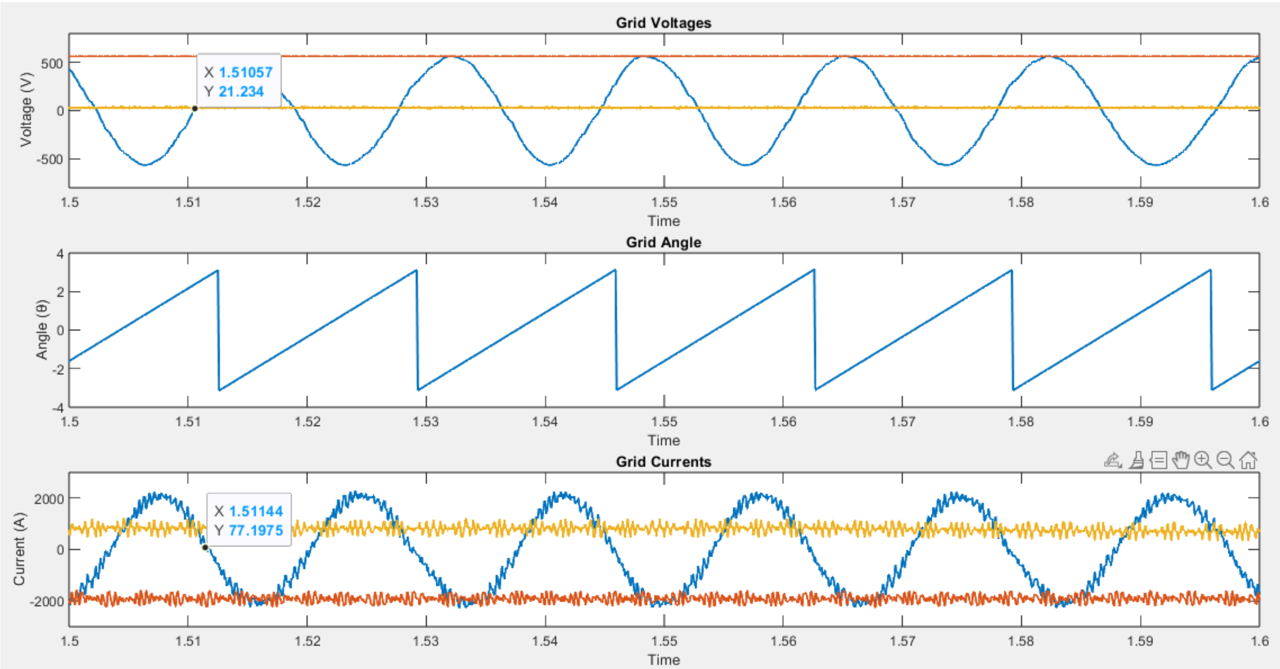

Fig. 8 Steady State -3 Grid Voltage (V_{ag}, V_{dg}, V_{qg}), Grid Angle (θ_g) and Grid Currents (I_{ag}, I_{dg}, I_{qg})

Explanation:

In fig 8. waveform, we can see that the values i_{ag} is leading ahead from v_{ag}. So, we can get the power factor as follows:

$$\theta = (1.5114 - 1.5105) \times 360 \ \times 60 = 19.44 \ or \ 199.44$$

As the value of reactive power is positive (Q_g = - 0.7749 MVAR) and power factor angle is between 180 and 270. Using the phase diagram given in project instruction, we can see that the power factor angle is in second quadrant with leading power factor.

Task-3: SPWM Waveforms

Steady State-1

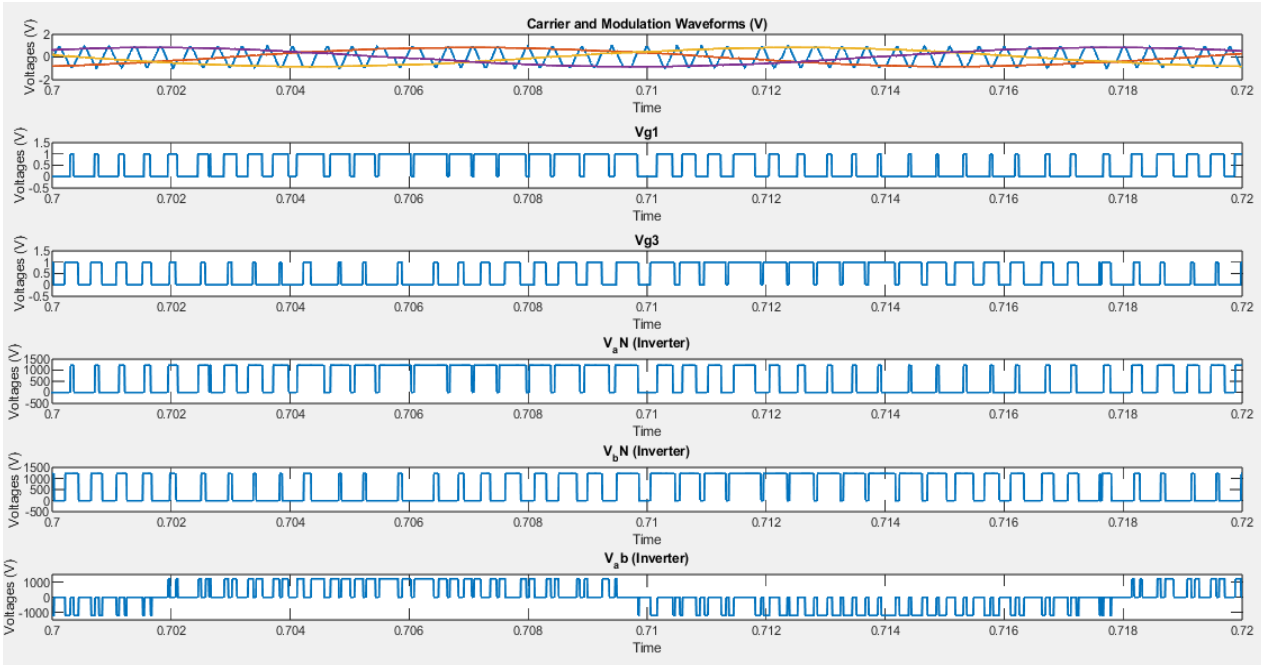

Fig. 9 Steady State -1 SPWM Waveforms

Steady State-2

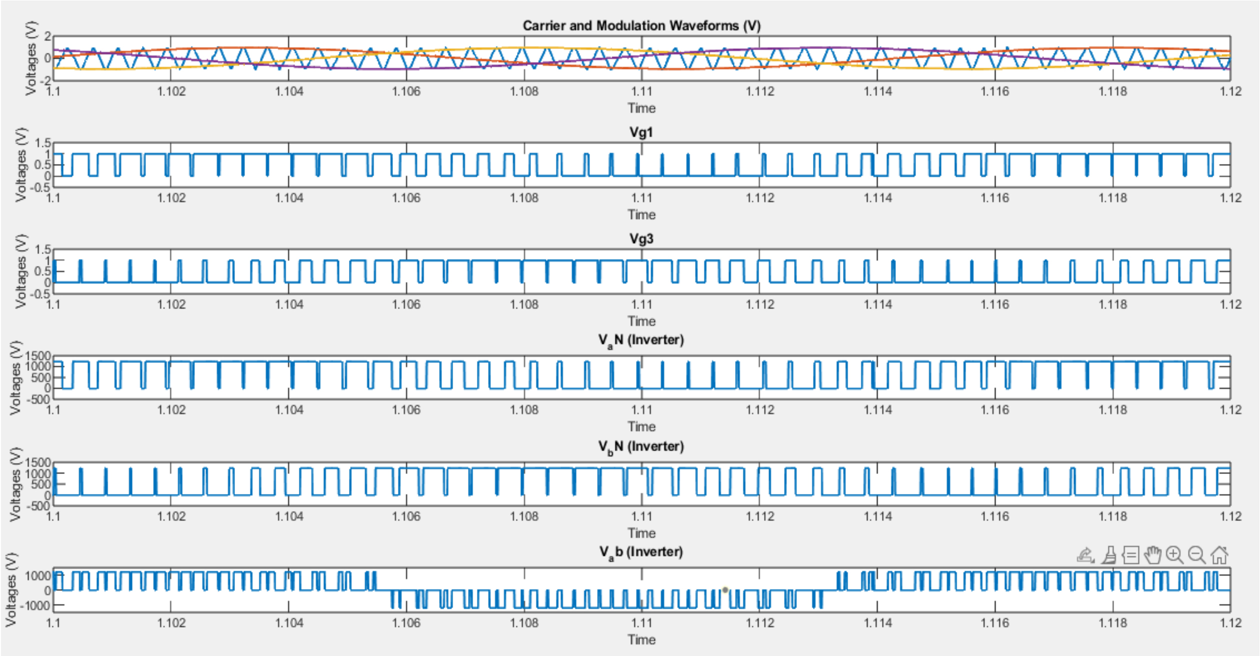

Fig. 10 Steady State -2 SPWM Waveforms

Steady State-3

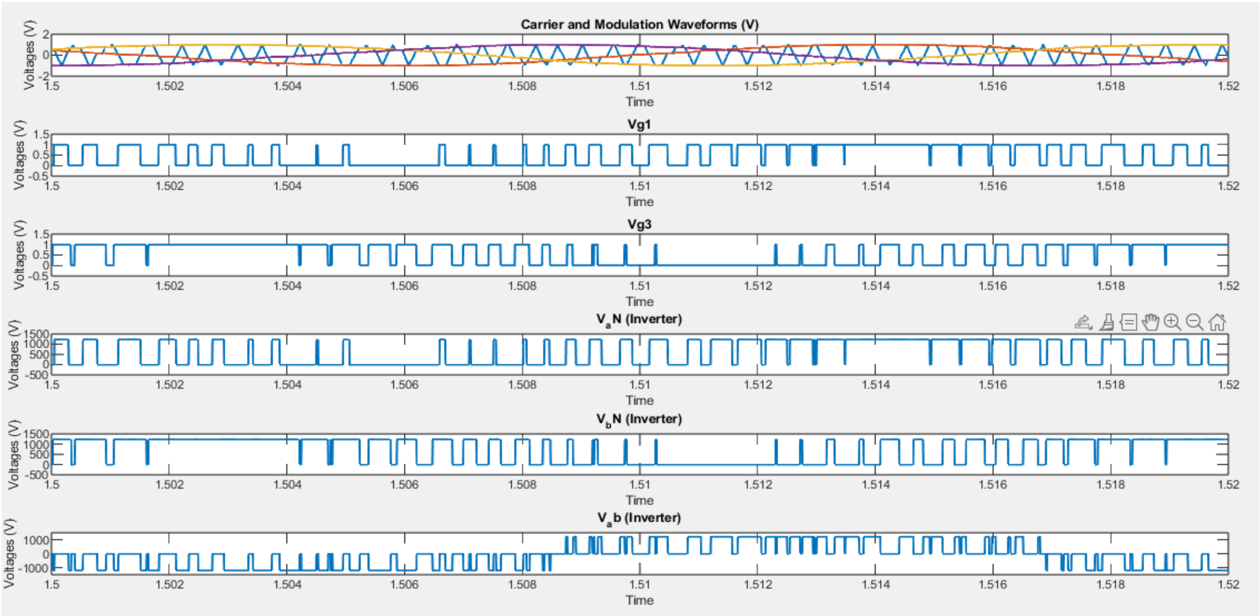

Fig. 11 Steady State -3 SPWM Waveforms

Explanation:

In steady-state operation, SPWM waveforms on the inverter side maintain a similar pattern and switching frequency. While comparison equation shown below likely controls switch gating based on phase-to-neutral voltages (V_{an}, V_{bn}), calculating the inverter's line-to-line voltage (V_{ab}) requires a different approach. For balanced systems, $V_{ab} = V_{an} - V_{bn}$, highlighting the relationship between these voltages. The value of V_a^*, V_b^*, V_c^* depends on the reference reactive power[1].

$$V_{cr} \leq V_a^* \rightarrow V_{g1} = 1, V_{g2} = 0$$

$$V_{cr} \leq V_b^* \rightarrow V_{g3} = 1, V_{g4} = 0$$

$$V_{cr} \leq V_c^* \rightarrow V_{g5} = 1, V_{g6} = 0$$

In waveforms, we can see that all the steady state waveforms are approximately same. We can observe that when V_{g1} is high then V_{an} will be set to high and when V_{g3} is high then V_{bn} will be set to high. While V_{ab} can be calculated using V_{an} and V_{bn}.

Task-4: Comparison between Simulated Data and Calculated Data

TABLE 2. Comparison between simulated values and calculated values

Parameter	**Steady State - 1**		**Steady State - 2**		**Steady State - 3**	
	Measured	**Calculated**	**Measured**	**Calculated**	**Measured**	**Calculated**
i_{dg} (A)	-2257	-1893.33	-2257	-1893.33	-2257	-1893.33
i_{qg} (A)	-1685	-1420	0	0	988.22	916.96
i_{ag}(Peak) (A)	2472	2366.66	2144.62	1893.33	2243.34	2103.69
$S_g(MVA)$	1.62	2	1.356	1.6	1.48	1.77
PF angle θ_g (Degrees)	-36.74	-36.86	0	0	23.64	25.84
Power Factor $cos\theta_g$	0.8013	0.8001	1	1	0.916	0.9

Task-5: FFT Analysis

Steady State - 1

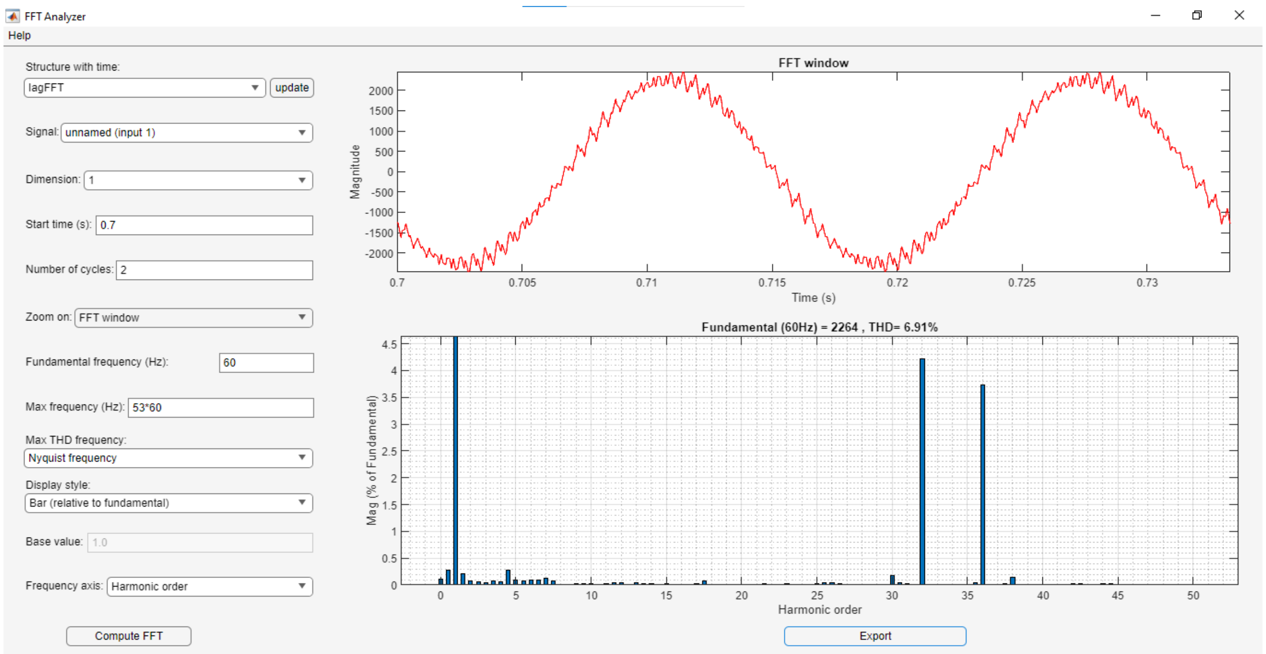

Fig. 12 Steady State -1 FFT Analysis

Steady State - 2

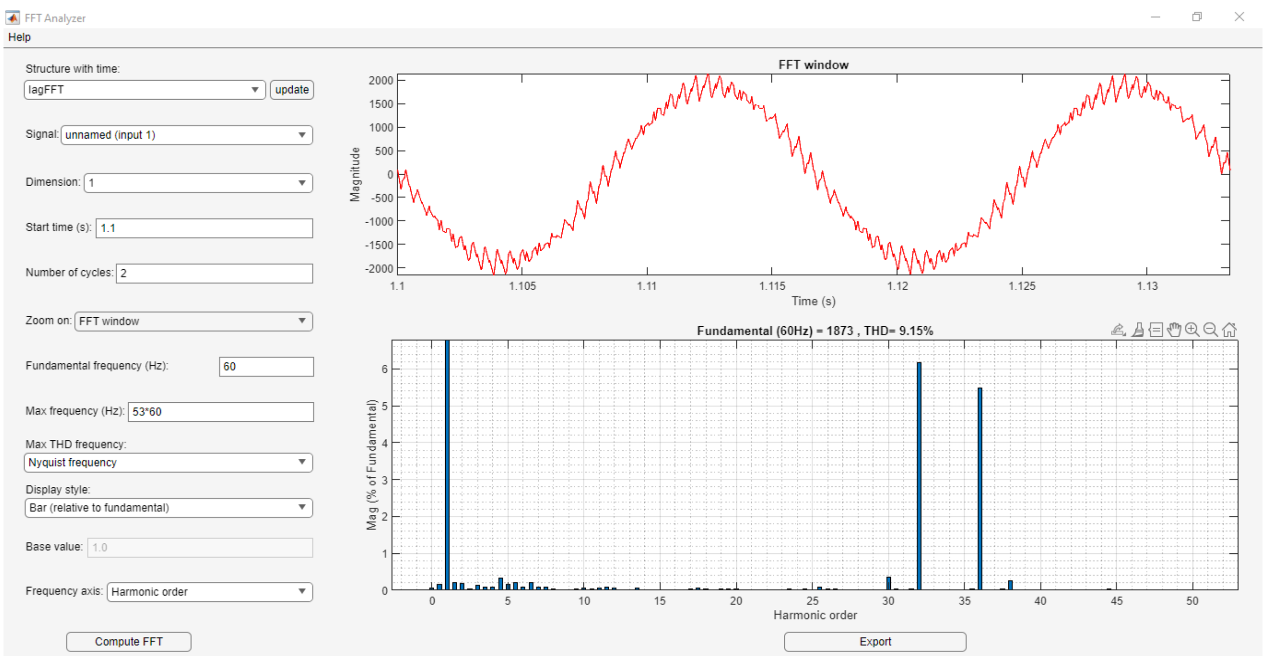

Fig. 13 Steady State -2 FFT Analysis

Steady State – 3

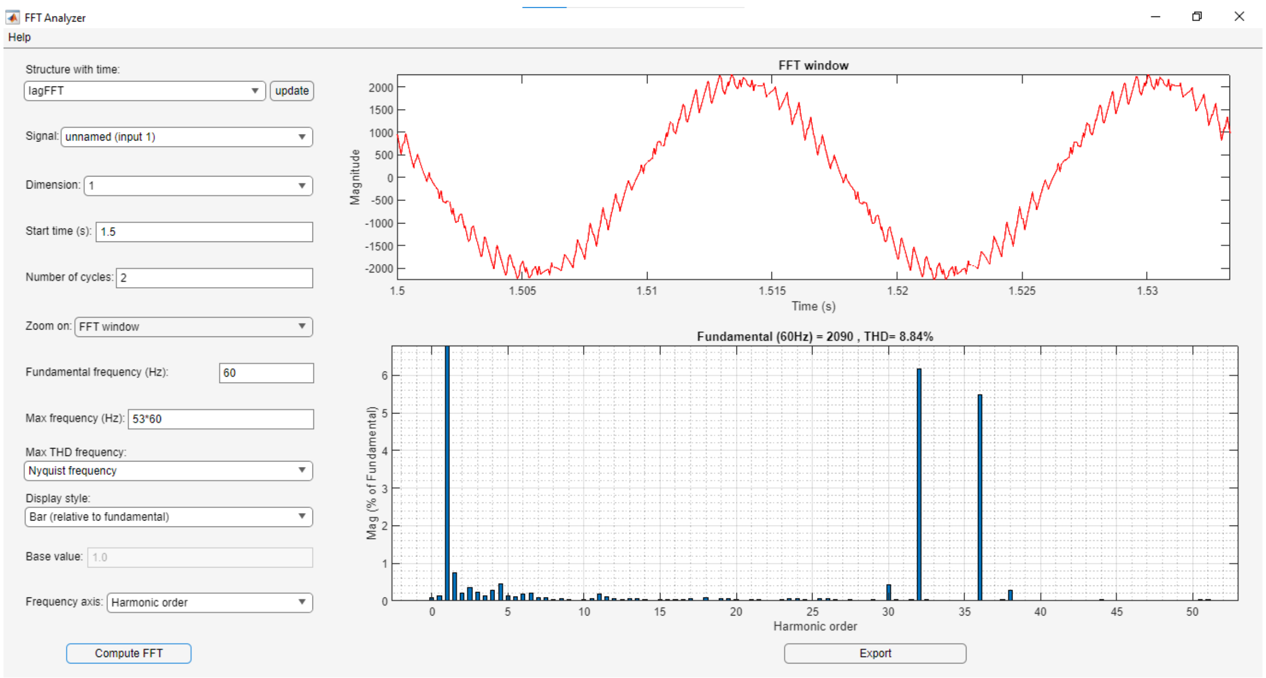

Fig. 14 Steady State -3 FFT Analysis

Explanation:

In fig. 12, 13, 14, we are observing the harmonic characteristics of inverter. This harmonic distortion is a function of modulation index. We can see the similar pattern as we have observed in modulation index. We can observe that, in steady state – 1, the Total Harmonic Distortion (THD) is 6.91%, For steady state - 2 and steady state – 3, the values of THD are 9.15% and 8.84% respectively.

B. Calculations

$$v_g = \left(\frac{690}{\sqrt{3}}\right) \times \sqrt{2} = 563.38$$

$$v_{dg} = v_g$$

Steady State – 1

$$i_{dg} = \frac{P_g}{1.5 \times v_g} = \frac{-1.6\ \times 10^6}{1.5\ \times\ 563.38} = \ -1893.33$$

$$i_{qg} = \frac{Q_g}{-\ 1.5 \times v_g} = \frac{1.2\ \times 10^6}{-1.5\ \times 563.38} = -1420$$

$$i_{ag} = \sqrt{i_{qg}^2 + i_{dg}^2} = \sqrt{(1420)^2 + (-1893.33)^2} = 2366.66$$

$$S_g = \sqrt{P_g^2 + Q_g^2} = \sqrt{(-1.6 \times 10^6)^2 + (1.2 \times 10^6)^2} = 2 \times 10^6$$

$$\phi_g = \tan^{-1}\left(\frac{Q_g}{P_g}\right) = \tan^{-1}\left(\frac{1.2}{-1.6}\right) = -36.86$$

Steady State – 2

$$i_{dg} = \frac{P_g}{1.5 \times v_g} = \frac{-1.6 \times 10^6}{1.5 \times 563.38} = -1893.33$$

$$i_{qg} = \frac{Q_g}{-1.5 \times v_g} = \frac{0}{-1.5 \times 563.38} = 0$$

$$i_{ag} = \sqrt{i_{qg}^2 + i_{dg}^2} = \sqrt{(0)^2 + (-1893.33)^2} = 1893.33$$

$$S_g = \sqrt{P_g^2 + Q_g^2} = \sqrt{(-1.6 \times 10^6)^2 + (0)^2} = 1.6 \times 10^6$$

$$\phi_g = \tan^{-1}\left(\frac{Q_g}{P_g}\right) = 0$$

Steady State – 3

$$i_{dg} = \frac{P_g}{1.5 \times v_g} = \frac{-1.6 \times 10^6}{1.5 \times 563.38} = -1893.33$$

$$i_{qg} = \frac{Q_g}{-1.5 \times v_g} = \frac{-0.7749 \times 10^6}{-1.5 \times 563.38} = 916.96$$

$$i_{ag} = \sqrt{i_{qg}^2 + i_{dg}^2} = \sqrt{(916.96)^2 + (-1893.33)^2} = 2103.69$$

$$S_g = \sqrt{P_g^2 + Q_g^2} = \sqrt{(-1.6 \times 10^6)^2 + (-0.7749 \times 10^6)^2} = 1.77 \times 10^6$$

$$\phi_g = \tan^{-1}\left(\frac{Q_g}{P_g}\right) = \tan^{-1}\left(\frac{-0.7749}{-1.6}\right) = 25.84$$

III. PROJECT QUESTIONS

Q1. What is the function of PLL used in the VOC model? What is the nature of variables (sinusoidal or DC) in stationary and synchronous frame?
Ans) The function of PLL (Phase Locked Loop) in the VOC (Voltage Oriented Controller is to measure the grid voltage angle (θ_g)[2]. As grid voltage angle (θ_g) is used to calculate the stationary to synchronous (abc/dq) transformation or synchronous to stationary (dq/abc) transformation. In abc reference frame, we have AC (sinusoidal) nature variables, whereas in dq reference frame, we have DC nature variables[3].

Q2. What is the essence of decoupled PI controller in VOC? What happens if the normal PI controller is used?
Ans) In the normal PI controller [2],

$$\begin{cases} \dfrac{di_{dg}}{dt} = \left(v_{dg} - v_{di} + \omega_g L_g \, i_{qg}\right) / L_g \\ \dfrac{di_{qg}}{dt} = \left(v_{qg} - v_{qi} - \omega_g L_g \, i_{dg}\right) / L_g \end{cases}$$

As we can see that the derivative of d-axis line current (i_{dg}) is related to both d-axis and q-axis variables[2]. This shows that the system is cross coupled which will lead to difficulties in controller design and performance. On the other hand, a decoupled controller solves this problem.

$$\begin{cases} \dfrac{di_{dg}}{dt} = \left(k_1 + k_2 / S\right)\left(i_{dg}^{*} - i_{dg}\right) / L_g \\ \dfrac{di_{qg}}{dt} = \left(k_1 + k_2 / S\right)\left(i_{qg}^{*} - i_{qg}\right) / L_g \end{cases}$$

In the above equation, we can see that d-axis line current (i_{dg}) is related to only d-axis variables[2]. So, now it is decoupled. This makes the system more convenient and stable.

Q3. For a 2 MVA inverter, what is the maximum reactive power that can be supplied? Under this condition, what is the maximum active power that can be transferable to the grid?
Ans) For 2 MVA inverter, we would consider maximum active power as +1.6 MW, then the maximum reactive power can be calculated as follows[3]:

$$S^2 = P^2 + Q^2$$

$$Q^2 = \sqrt{s^2 - P^2} = \sqrt{2^2 - 1.6^2} = 1.2\ MVAR$$

Q4. Which modulation method (SVM or SPWM) utilizes dc-link voltage more efficiently? Comment on the percentage improvement of dc-link utilization?
Ans) In inverter applications, Sinusoidal Pulse Width Modulation (SPWM) generally demonstrates superior efficiency in utilizing the DC-link voltage compared to Space Vector Modulation (SVM). This advantage stems from SPWM's ability to generate fewer switching transitions within the inverter, thereby minimizing switching losses. The resulting improvement in DC-link voltage efficiency can range from 5% to 15% or even higher, depending on the specific characteristics of the system. However, the selection between SPWM and SVM requires careful consideration of other factors beyond efficiency, such as the level of harmonic distortion introduced into the output waveform and the relative complexity of implementation for each modulation technique.

Q5. The decoupled VOC model given in this lab is for low-voltage (690 V) grid connection. If three-level converters are used for medium-voltage (3000 V) grid-connection, does this VOC model work? Justify your explanation.
Ans) When utilizing three-level converters for medium-voltage (3000V) applications, the conventional Voltage-Oriented Control (VOC) model designed for low-voltage (690V) grids may not operate effectively. The VOC model relies on active power flowing from the inverter to the grid, necessitating negative power. However, in the context of three-level converters, the DC-link voltage (V_{dc}) tends to be lower than the grid voltage (E), resulting in positive active power flow from the grid to the inverter. This mismatch in voltage levels disrupts the intended power flow, rendering the VOC model incompatible with such configurations. Therefore, adaptations are required to ensure the VOC model's effectiveness for medium-voltage grid connections.

IV. CONCLUSION

In conclusion, this project has provided valuable insights into the operation and control of grid-tied inverters, particularly focusing on Voltage-Oriented Control (VOC) with a decoupling controller. Through our investigation, we have gained a better understanding of how these inverters function and how their performance can be enhanced using advanced control techniques. By designing a sinusoidal pulse width modulation scheme tailored for grid-tied inverters, we have laid the groundwork for more efficient and reliable electricity generation. Additionally, our study on active and reactive power control has shed light on strategies to optimize power management and ensure seamless integration with the grid. Overall, the findings of this project contribute to the ongoing efforts in improving the functionality and effectiveness of grid-tied inverter systems in modern power networks.

V. REFERENCES

[1] Prof. Apparao Dekka, “Project Instructions.”
[2] B. Wu, Y. Lang, N. Zargari, and S. Kouro, *Power Conversion and Control of Wind Energy Systems*. 2011. doi: 10.1002/9781118029008.
[3] Prof. Apparao Dekka, “Lecture Slides.”

VI. APPENDIX

1. Three Phase Grid

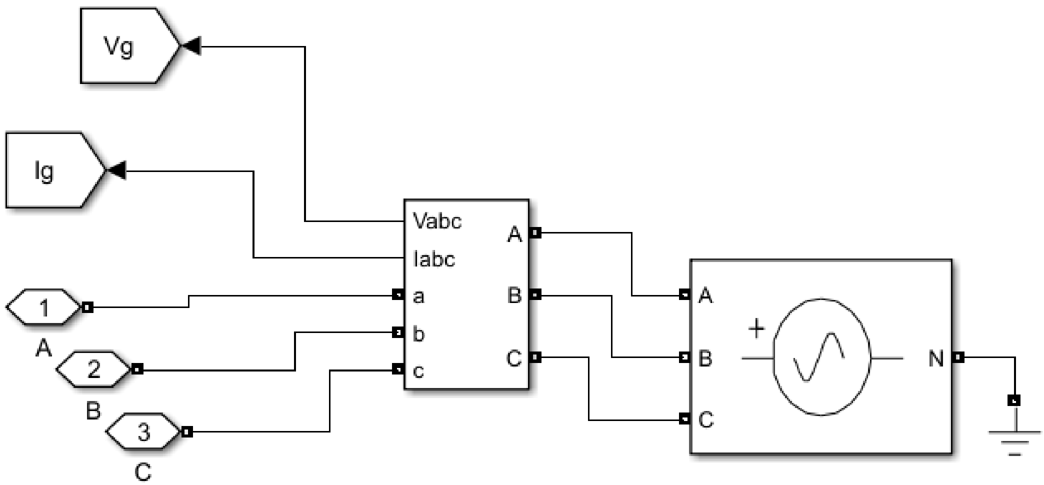

Fig. 15 Three Phase Grid

2. Decoupled Voltage Oriented Controller

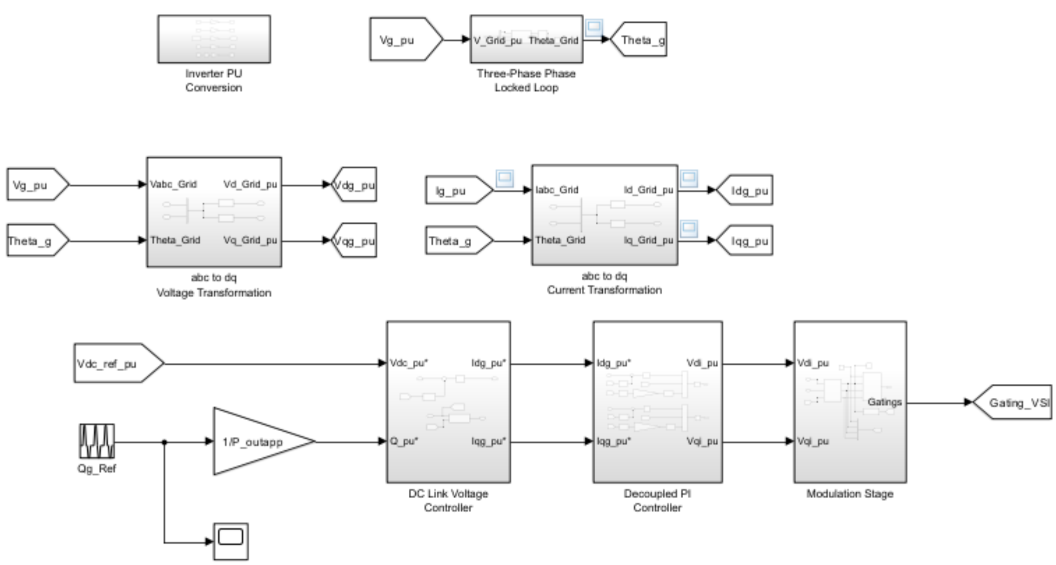

Fig. 16 Decoupled Voltage Oriented Controller

3. Inverter PU Conversion

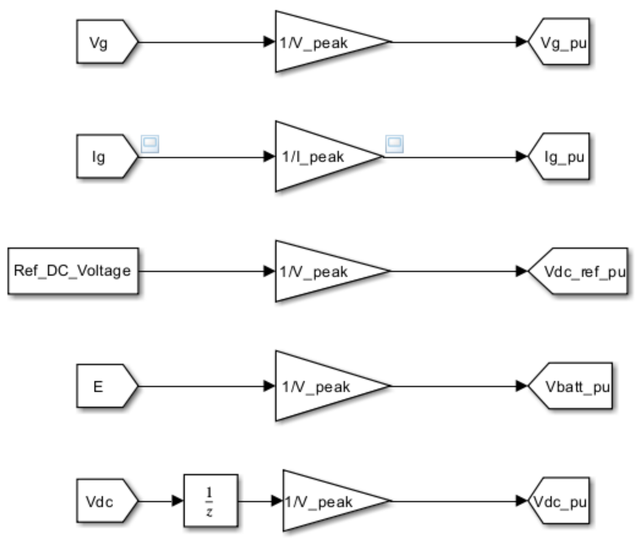

Fig. 17 Inverter PU Conversion

4. Phase Lock-Loop Subsystem

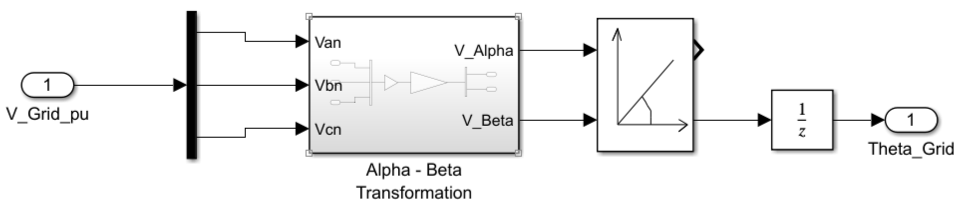

Fig. 18 PLL Subsystem

5. abc/dq Transformation

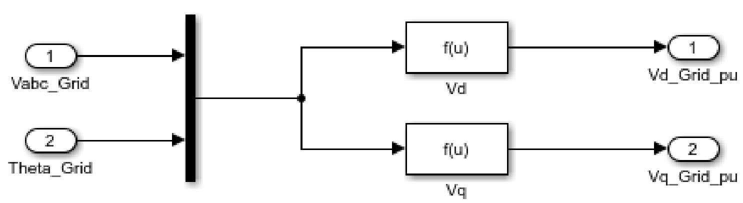

Fig. 19 abc/dq Transformation for voltage

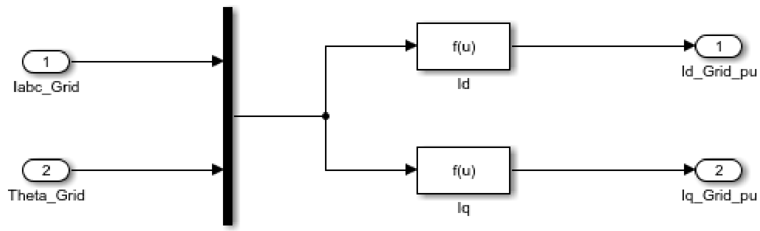

Fig. 20 abc/dq Transformation for current

6. DC-Link Voltage Controller

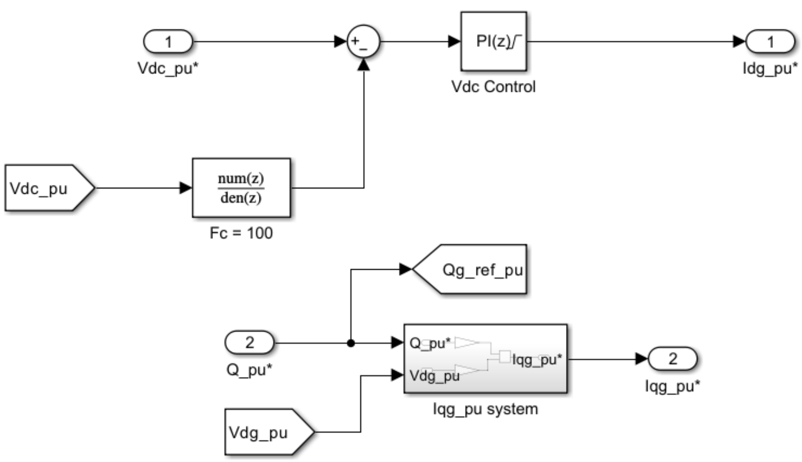

Fig. 21 DC-Link Voltage Controller

7. Decoupled PI Controller

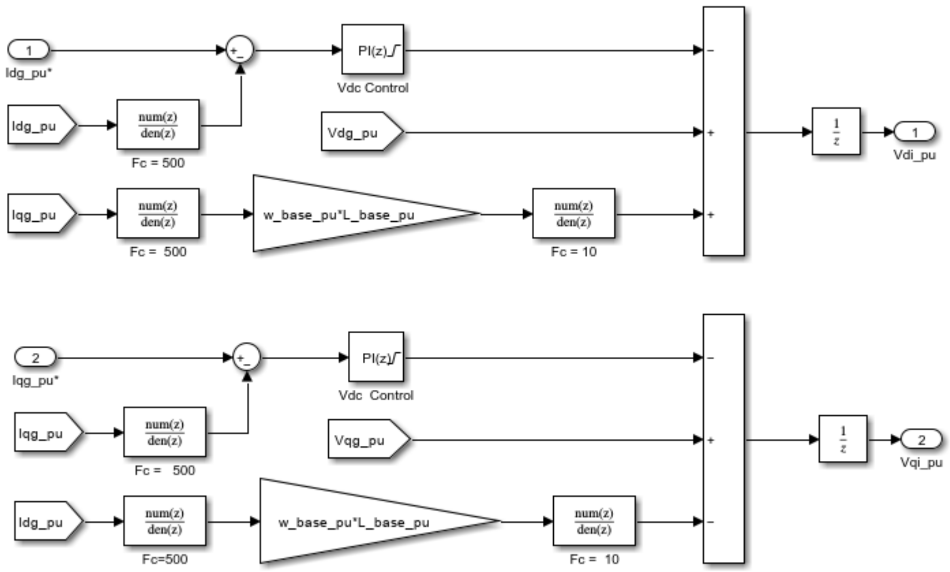

Fig. 22 Decoupled PI Controller

8. Modulation Stage

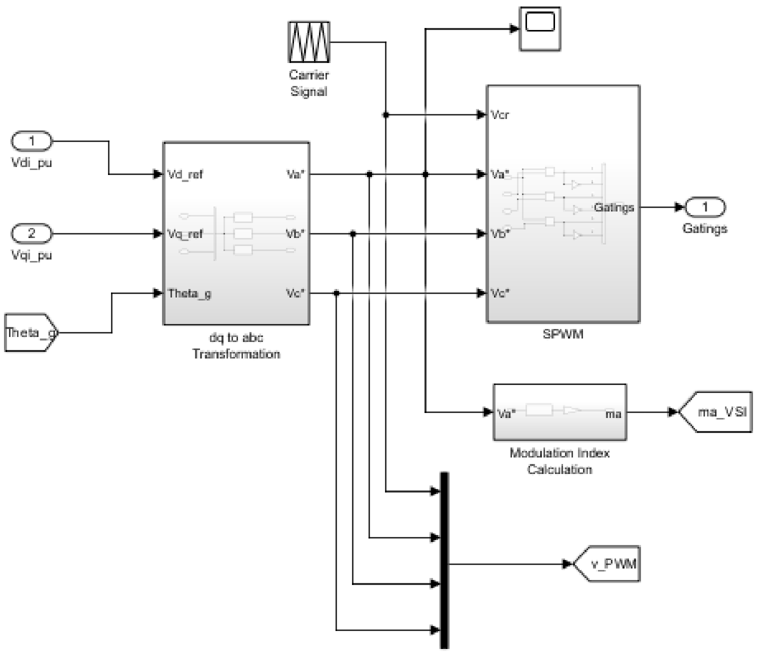

Fig. 23 Modulation Stage

9. dq/abc Transformation

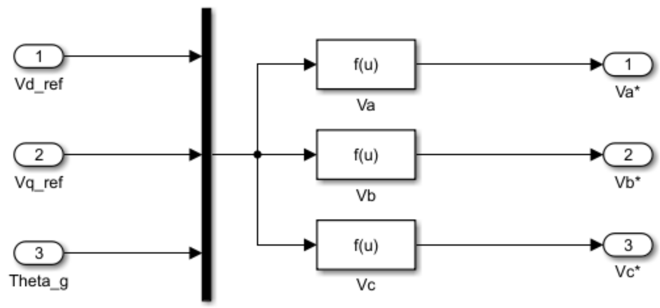

Fig. 24 dq/abc Transformation

10. SPWM

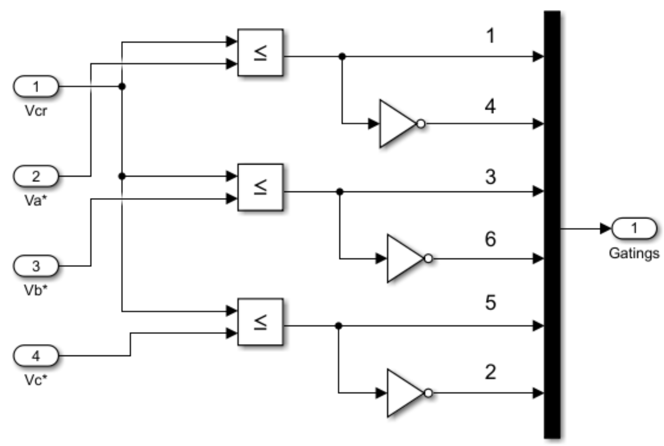

Fig. 25 SPWM

11. RMS Calculation for Modulation Index

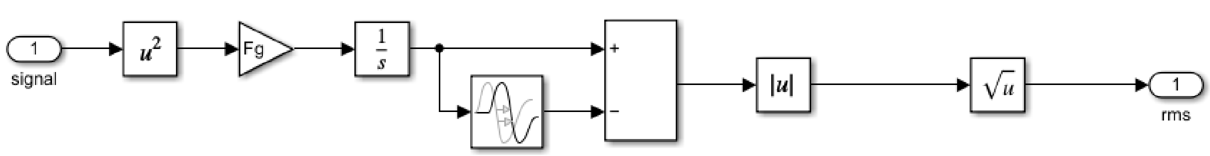

Fig. 26 RMS Calculation for Modulation Index

Code:

Part 1: For Passing the constant values to Simulink Model

```
clc;
clear all;
close all;

%Parameters
P_outapp = 2.00e+06; %Rated inverter output apparent power
Grid_Filter_Res = 1.19025e-03; %Grid filter parameters
Grid_Filter_Ind = 0.12629e-03; %Grid filter parameters
Voltage_Battery = 1259; %Battery voltage
Ref_DC_Voltage = 1220; %Reference DC voltage
DC_Link_Cap = 44571.853e-06; %DC-link capacitor
DC_Link_Res = 30e-03; %DC-link resistor
F_swg = 2040; %Switching frequency
F_sampg = 10000; %Sampling frequency
Grid_Line_RMS_Voltage = 690; %Grid line-line rms voltage
Fg = 60; %Grid frequency
Active_Power_Grid = 1.6e+06; %Active power delivered to the grid

%Base Values Calculation
P_outapp_base = P_outapp; %Base Apparent Power
Fg_base = Fg; %Base Frequency
Voltage_base = (Grid_Line_RMS_Voltage)/(sqrt(3)); %Base Voltage
Current_base = P_outapp_base/(3*Voltage_base); %Base Current
w_base = 2*pi*Fg_base; %Base Speed(rad/sec)
Z_base = Voltage_base/Current_base; %Base Impedance
L_base = Z_base/(w_base); %Base Inductance
C_base = 1/(Z_base*w_base); %Base Capacitance

%Peak Base Calculation
V_peak = sqrt(2)*Voltage_base;
I_peak = sqrt(2)*Current_base;

%Alpha to Beta Conversion
alpha_beta = [1 (-1/2) (-1/2); 0 (sqrt(3)/2) (-sqrt(3)/2)];

%Cutoff Frequency
Fc = 100;
Fc1 = 500;
Fc2 = 10;

%Sample Time for conditional display of parameter
Ts = 1/F_sampg;

%Per unit Calculation
w_base_pu = 1;
L_base_pu = 0.2;
```

Part 2: For plotting graph for different parameters

```
clc;
tout = transpose(0: 0.0000062471:2); %For all values
% Task 1 Plots
t = transpose(0:0.0001:2); %For Grid Angle Vector Size
% Part 1 Plots
subplot(311);
plot(tout, Grid_Voltages, 'LineWidth',1.5);
ylim([-800 800]);
xlabel("Time");ylabel("Voltage (V)");title("Grid Voltages");
subplot(312);
plot(t, Theta_g, 'LineWidth',1.5);
ylim([-4 4]);
xlabel("Time");ylabel("Angle (θ)");title("Grid Angle");
subplot(313);
plot(tout, Grid_Current, 'LineWidth',1.5);
ylim([-3000 3000]);
xlabel("Time");ylabel("Current (A)");title("Grid Currents");

% Part 2 Plots
% subplot(311);
% plot(tout, DC_Voltages, 'LineWidth',1.5);
% ylim([1180 1280]);
% xlabel("Time");ylabel("Voltage (V)");title("DC-Link Voltages");
% subplot(312);
% plot(tout, ma_VSI, 'LineWidth',1.5);
% ylim([0.6 1.2]);
% xlabel("Time");ylabel("Index");title("Modulation Index");
% subplot(313);
% plot(tout, Grid_Powers, 'LineWidth',1.5);
% ylim([-3 3]);
% xlabel("Time");ylabel("Power (MW, MVA, MVAR)");title("Grid Powers");

% Task 2 Plots

% Steady State - 1
% t = transpose(0:0.0001:2); %For Grid Angle Vector Size
% subplot(311);
% plot(tout, Grid_Voltages, 'LineWidth',1.5);
% ylim([-800 800]); xlim([0.7 0.75]);
% xlabel("Time");ylabel("Voltage (V)");title("Grid Voltages");
% subplot(312);
% plot(t, Theta_g, 'LineWidth',1.5);
% ylim([-4 4]); xlim([0.7 0.75]);
% xlabel("Time");ylabel("Angle (θ)");title("Grid Angle");
% subplot(313);
% plot(tout, Grid_Current, 'LineWidth',1.5);
```

```
% ylim([-3000 3000]); xlim([0.7 0.75]);
% xlabel("Time");ylabel("Current (A)");title("Grid Currents");

% Steady State - 2
% t = transpose(0:0.0001:2); %For Grid Angle Vector Size
% subplot(311);
% plot(tout, Grid_Voltages, 'LineWidth',1.5);
% ylim([-800 800]); xlim([1.1 1.2]);
% xlabel("Time");ylabel("Voltage (V)");title("Grid Voltages");
% subplot(312);
% plot(t, Theta_g, 'LineWidth',1.5);
% ylim([-4 4]); xlim([1.1 1.2]);
% xlabel("Time");ylabel("Angle (θ)");title("Grid Angle");
% subplot(313);
% plot(tout, Grid_Current, 'LineWidth',1.5);
% ylim([-3000 3000]); xlim([1.1 1.2]);
% xlabel("Time");ylabel("Current (A)");title("Grid Currents");

% Steady State - 3
% t = transpose(0:0.0001:2); %For Grid Angle Vector Size
% subplot(311);
% plot(tout, Grid_Voltages, 'LineWidth',1.5);
% ylim([-800 800]); xlim([1.5 1.6]);
% xlabel("Time");ylabel("Voltage (V)");title("Grid Voltages");
% subplot(312);
% plot(t, Theta_g, 'LineWidth',1.5);
% ylim([-4 4]); xlim([1.5 1.6]);
% xlabel("Time");ylabel("Angle (θ)");title("Grid Angle");
% subplot(313);
% plot(tout, Grid_Current, 'LineWidth',1.5);
% ylim([-3000 3000]); xlim([1.5 1.6]);
% xlabel("Time");ylabel("Current (A)");title("Grid Currents");

% Task 3 SPWM Plots

% Steady State - 1
% subplot(611);
% plot(tout, v_PWM, 'LineWidth',1.5);
% ylim([-2 2]); xlim([0.7 0.72]);
% xlabel("Time");ylabel("Voltages (V)");title("Carrier and Modulation Waveforms (V)");
% subplot(612);
% plot(tout, vg1, 'LineWidth',1.5);
% ylim([-0.5 1.5]); xlim([0.7 0.72]);
% xlabel("Time");ylabel("Voltages (V)");title("Vg1");
% subplot(613);
% plot(tout, vg3, 'LineWidth',1.5);
% ylim([-0.5 1.5]); xlim([0.7 0.72]);
% xlabel("Time");ylabel("Voltages (V)");title("Vg3");
% subplot(614);
% plot(tout, v_aN, 'LineWidth',1.5);
% ylim([-500 1500]); xlim([0.7 0.72]);
% xlabel("Time");ylabel("Voltages (V)");title("V_aN (Inverter)");
```

```
% subplot(615);
% plot(tout, v_bN, 'LineWidth',1.5);
% ylim([-500 1500]); xlim([0.7 0.72]);
% xlabel("Time");ylabel("Voltages (V)");title("V_bN (Inverter)");
% subplot(616);
% plot(tout, V_ab, 'LineWidth',1.5);
% ylim([-1500 1500]); xlim([0.7 0.72]);
% xlabel("Time");ylabel("Voltages (V)");title("V_ab (Inverter)");

% Steady State - 2
% subplot(611);
% plot(tout, v_PWM, 'LineWidth',1.5);
% ylim([-2 2]); xlim([1.1 1.12]);
% xlabel("Time");ylabel("Voltages (V)");title("Carrier and Modulation Waveforms (V)");
% subplot(612);
% plot(tout, vg1, 'LineWidth',1.5);
% ylim([-0.5 1.5]); xlim([1.1 1.12]);
% xlabel("Time");ylabel("Voltages (V)");title("Vg1");
% subplot(613);
% plot(tout, vg3, 'LineWidth',1.5);
% ylim([-0.5 1.5]); xlim([1.1 1.12]);
% xlabel("Time");ylabel("Voltages (V)");title("Vg3");
% subplot(614);
% plot(tout, v_aN, 'LineWidth',1.5);
% ylim([-500 1500]); xlim([1.1 1.12]);
% xlabel("Time");ylabel("Voltages (V)");title("V_aN (Inverter)");
% subplot(615);
% plot(tout, v_bN, 'LineWidth',1.5);
% ylim([-500 1500]); xlim([1.1 1.12]);
% xlabel("Time");ylabel("Voltages (V)");title("V_bN (Inverter)");
% subplot(616);
% plot(tout, V_ab, 'LineWidth',1.5);
% ylim([-1500 1500]); xlim([1.1 1.12]);
% xlabel("Time");ylabel("Voltages (V)");title("V_ab (Inverter)");

% Steady State - 3
% subplot(611);
% plot(tout, v_PWM, 'LineWidth',1.5);
% ylim([-2 2]); xlim([1.5 1.52]);
% xlabel("Time");ylabel("Voltages (V)");title("Carrier and Modulation Waveforms (V)");
% subplot(612);
% plot(tout, vg1, 'LineWidth',1.5);
% ylim([-0.5 1.5]); xlim([1.5 1.52]);
% xlabel("Time");ylabel("Voltages (V)");title("Vg1");
% subplot(613);
% plot(tout, vg3, 'LineWidth',1.5);
% ylim([-0.5 1.5]); xlim([1.5 1.52]);
% xlabel("Time");ylabel("Voltages (V)");title("Vg3");
% subplot(614);
% plot(tout, v_aN, 'LineWidth',1.5);
% ylim([-500 1500]); xlim([1.5 1.52]);
% xlabel("Time");ylabel("Voltages (V)");title("V_aN (Inverter)");
```

```
% subplot(615);
% plot(tout, v_bN, 'LineWidth',1.5);
% ylim([-500 1500]); xlim([1.5 1.52]);
% xlabel("Time");ylabel("Voltages (V)");title("V_bN (Inverter)");
% subplot(616);
% plot(tout, V_ab, 'LineWidth',1.5);
% ylim([-1500 1500]); xlim([1.5 1.52]);
% xlabel("Time");ylabel("Voltages (V)");title("V_ab (Inverter)");
```

In plot code, as per requirement values code will be un-commented and plot will be displayed.