A

Project Report

On

"ACTIVE AND REACTIVE POWER CONTROL FOR THREE PHASE INVERTER"

Submitted in partial fulfilment of the requirements

of the degree of

Bachelor of Engineering in Electrical Engineering

Submitted by

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DECLARATION

I declare that this written submission represents my ideas in my own words and where others ideas or words have been included; I have adequately cited and referenced the original sources. I also declared that I have adhered to all principles of academic honesty and integrity and have not represented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission have not been taken when needed.

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Abstract

At present scenario, renewable energy sources become an alternative source of energy for future energy demand and to mitigate environment pollution problems. Grid connected renewable energy source like wind energy system uses power electronics converters as an interfacing device between wind energy system and utility grid. These converters are commonly based on a voltage source inverter (VSI) connected to the supply network, operated to achieve objectives such as power flow regulation with unity power factor operation. However, intermittent nature of wind energy must be controlled to meet the grid requirements. The grid requirements include independent control of active & reactive power, improved power quality, grid synchronization and Good transient response during fault conditions etc. Usually voltage oriented control (VOC) of grid side converter in the synchronous reference frame was universally adapted for independent control of active and reactive power of the grid. However, the dynamic response during abnormal condition of grid is sluggish and poor power quality. In order to design controller for robust performance and to know the control characteristics, VSI needs to be accurately modelled. This project has taken an attempt to derive the small signal model of a single phase inverter in isolated mode and its performance with different controllers. Further, the work is extended to modelling of three phase grid connected VSI and its relevant transfer functions have been deduced from the model so as to analyse the system performance for designing a controller through well known bode plots. The studied system is modelled and simulated in the MATLAB-Simulink environment..

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the sources and grid. The role of input side converter is to extract the maximum power from the renewable source and to provide the power to grid side converter. The role of grid side converter is to control the power flow to the grid and to maintain the output voltage and frequency at the desired level. The system is synchronized with the grid through a filter known as grid filters. These filters require high switching frequencies to acceptably attenuate switching harmonics particularly in weak grid where the grid voltage is sensitive to load variations. In most cases control design for the three phase PWM inverter involves two steps and these are choice of modulation strategy which corresponds to open loop control and design of dynamic close loop control. However, reactive power control is one of the key issues to deal with in DPGS. From the investigation of the blackout occurred in U.S. and Canada in 2003 it was found that the cascaded outages of several transmission lines and generating units could have been avoided if controllable reactive power was available [3].

This project has taken an attempt to derive the small signal model of a single phase inverter in isolated mode and its performance with different controllers. Further, the work is extended to Modelling of three phase grid connected VSI and its relevant transfer functions have been deduced from the model so as to analyze the system performance for designing a controller through well-known bode plots. The studied system is modeled and simulated in the MATLAB-Simulink environment.

1.2 Research Motivation

In recent years availability of power in India has both increased and improved but demand has consistently outstripped supply and substantial energy and peak shortages prevailed in 2009-10. Due to economic viability wind energy has become promising source of renewable energy. Now India has become fifth in installed capacity of wind power plant. As of 31st march the installed capacity of wind power in India was 17967MW [4]. But, as the wind is season and region based, it was not so reliable as long as Power Electronics had not been advanced much. Now-a-days the interface of Power Electronics has made wind energy system one of the reliable sources. Still there are some problems regarding stability and synchronization with utility grid, which has been improved by employing new control algorithms to switch the PWM based voltage source inverter used in it. An attempt is initiated to improve the control of Grid side inverter in this project.

1.3 Literature Review

Grid connected inverter system employes different control algorithm in order to improve the over all system perfomance and the relevent control strategies are extensively studied in the available literature[1]-[18]. Average current control (ACC) has been widely used for controlling DC/DC as well as single-phase power factor correction (PFC) converters. Compared to peak current control ACC has following advantages[5].

- Error is minimized as a high gain current error amplifier is used.
- Large noise margin.
- No need of external compensation ramp.
- Easy current limit implementation.
- Good tracking performance of Average current mode control.

In order to design an average current control for an inverter, small signal modelling needs to be done which is based on average switched modelling [5]. In this technique manipulations are performed on the circuit rather than on its equations. The converter switches are replaced with voltage and current sources to obtain a time invariant circuit. Then the converter wave forms are averaged over one switching period to remove the undesired switching harmonics. Any non-linear elements present in the averaged circuit model can then be perturbed and linearized to represent small signal model [6]. In order to implement average current controller small signal modelling of inverter is required. This can be achieved by circuit averaging and as well as state space averaging. In [7] a state space averaging method is employed so as to get a small signal model. In [8] an average current mode controller is used to get equal current distribution in case of a resonant DC to DC converter. In average model of three phases inverter is proposed so as to reduce the current distributions in multi module Resonant dc to dc converter. However, in case of three phase grid connected inverter voltages and currents are usually transferred to rotating d-q reference frame for making design of controller easier because the current space vector in the rotating d-q reference frame is fixed, the PI controllers operate on dc, rather than sinusoidal signals. A new and simpler control technique is being employed in a grid connected inverter without applying the d-q transformation as reported in [9] which achieves zero steady state error in the stationary reference frame. A new predictive control algorithm for grid-connected current-controlled inverters is being employed in [10] which combine a two-sample deadbeat control law with a Luenberger observer to estimate the future value of the grid currents. The resulting control offers robustness against the computational delay inherent in the digital implementation and considerably enhances the gain and phase margins of the previous predictive controls while maintaining the high-speed response of the deadbeat controllers. A novel control for voltage-source inverters with the capability to flexibly operate in grid-connected and islanded modes was studied designed in [11] which are based on the droop method, which uses some estimated grid parameters such as the voltage and frequency and the magnitude and angle of the grid impedance. Hence, the inverter is able to inject independently controlled active and reactive power to the grid. The controller provides a proper dynamics decoupled from the grid-impedance magnitude and phase. The system is also able to control active and reactive power flows independently for a large range of impedance grid values. For controlling reactive power a new control strategy direct current d-q vector control has been proposed in [12] to overcome the shortage of the conventional vector control technique. Direct control technique differs from standard vector control technique in the generation of control variable. In the former case current is the tuned control variable and in latter case is the voltage. However, in almost all the cases of the control techniques of three phase grid connected inverter transformation to rotating co-ordinates have been employed but in [13] direct power control is followed which utilizes a non-linear sliding mode control in order to reduce the instantaneous power error to zero and this does not necessitate transformation to rotating co-ordinates. To design a controller for inverter transfer functions are to be derived and in order to accomplish that it is to be modeled. In [14] a single phase inverter in island mode is modeled as small signal model and then transfer functions are derived for designing an Average current controller (ACC) for it. A switching flow-graph (SFG) Modelling technique

[16] is used to build the large-signal model of a cascaded multilevel inverter. With the concept of virtual switch and virtual switching function proposed in SFG Modelling technique, the large-signal SFG model of a cascaded multilevel inverter can be derived easily and without complex mathematic works. A novel control method, named weighted average cur-rent control (WACC), is proposed for damping control of a three-phase grid inverter with an LC filter [17]. In this method, the sum of partial inverter current and partial grid current is

used as the feedback of the current control loop. By using WACC, three-phase current control of the grid inverter can be well decoupled under synchronous rotating frame. Furthermore, the system transfer function is reduced from the third-order system to the first-order system. Consequently, the control loop gain and bandwidth can be increased, which improve the rejection capability to the back-ground grid voltage harmonics.

1.4 Thesis Objectives

The ultimate aim of this study is to meet the following objectives:

- To extend small signal modelling to 3-Φ inverter.
- To study the active and reactive power calculation
- MATLAB implementation of proposed theory.

1.5 Thesis Organization

The organization of thesis is given as follows

CHAPTER 1 which describes the research motivation and related work done of proposed study. Also it advises the objectives of the proposed study.

CHAPTER 2 presents the modelling of 3-Φ grid connected inverter which involves two stages of modelling. One is power stage modelling and from the power stage model small signal model is derived which is based on same principle perturb and observe.

CHAPTER 3 presents the control loop design for both voltage and current and also the transfer functions are derived for stability study. The effect of resonance was observed from the bode plot of control to grid voltage transfer function. A control strategy is developed with step responses of the controller for effectiveness of the study.

CHAPTER 4 presents the simulation results which are being carried out in MATLAB/Simulink environment.

CHAPTER 5 presents the conclusion of work done and scope of the future work followed by references.

CHAPTER 2

2.1 Modelling of 3-Φ VSI

Three phase VSIs are used to interface between dc and ac systems in distributed power generation system. Different control techniques have been applied to the three phase grid connected VSI for the control of active and reactive power along with constant dc link voltage. However, designing a controller with help of a small signal model is a well-known practice in dc-dc converter. Transfer functions of the control variables need to be identified for designing a control system. The transfer functions are deduced using averaged switched modeling technique. In modern days power electronics converters are widely employed in all the applications. As the switches are involved in these applications, non-linearity occurs in the system. So the power stage must be linearized in order to design a linear feed-back control. In this work a three phase grid connected VSI with LC filter has been considered for modeling. As it is quite difficult to design a controller in case of three phase ac system, so first three phase ac system (abc) is transformed into synchronous rotating reference frame (dq) and the transformation is known as Park"s transformation [17]. The resulting model from the corresponding transformation is known as large signal model which involves dc quantities due to the transformation to the rotating reference frame.

The modeling of inverter involves two stages namely power stages modeling which is said to be large signal modeling and small signal modeling.

4.1.1. Power Stage Model

In power stage of model the power circuit, second order LC filter, grid and corresponding parameters are transformed in to synchronous rotating reference frame.

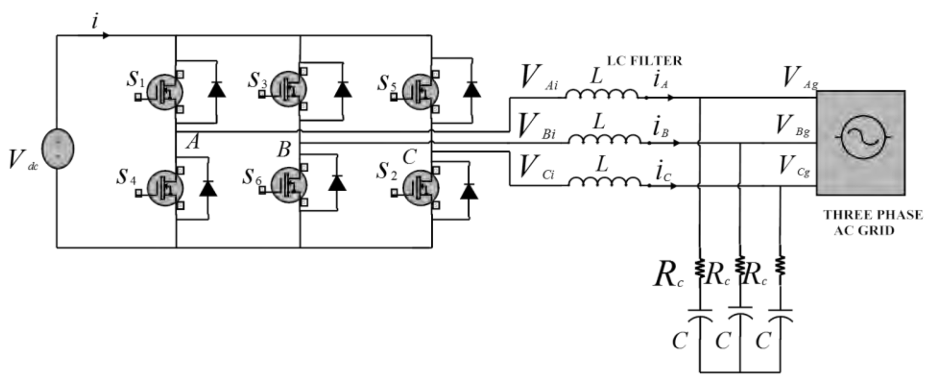


Fig.2.1 Schematic diagram of three phase grid connected VSI with LC filter

In Fig.4.1 three phase VSI is connected to the grid through a LC filter. V_{Ai},V_{Bi} ,V_{Ci} are the voltages at the inverter output and V_{Ag} ,V_{Bg}, V_{Cg} are the voltages at the grid end. By applying voltage balance equation

$$\Rightarrow \begin{bmatrix} V_{Ai} \\ V_{Bi} \\ V_{Ci} \end{bmatrix} = L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} V_{Ag} \\ V_{Bg} \\ V_{Cg} \end{bmatrix} \qquad 2.1$$

where L= inductance with negligible resistance.

By transforming the equation (2.1) into synchronous reference frame as given in Appendix A the following equation (2.2) is obtained.

$$\Rightarrow \begin{bmatrix} V_{di} \\ V_{qi} \end{bmatrix} = L\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} V_{dg} \\ V_{qg} \end{bmatrix} + \omega L\begin{bmatrix} -i_q \\ i_d \end{bmatrix} \qquad 2.2$$

As the inverter output voltage is a function of dc link voltage, the inverter dq-voltages are expressed as follows

$$\begin{bmatrix} V_{di} \\ V_{qi} \end{bmatrix} = \begin{bmatrix} d_d \\ d_q \end{bmatrix} V_{dc} \qquad 2.3$$

$$\& \quad i = [d_d \quad d_q].\begin{bmatrix} i_d \\ i_q \end{bmatrix} \qquad 2.4$$

Where V_{dc} is dc link voltage applied to the inverter and d_d and d_q are the duty cycles corresponding to the d- and q-axes respectively. By substituting value of equation (2.3) in equation (2.2), equations (2.5) and (2.6) are obtained

$$d_d.V_{dc} = L\frac{di_d}{dt} - \omega L i_q + V_{dg} \quad 2.5$$

$$d_q.V_{dc} = L\frac{di_q}{dt} + \omega L i_d + V_{qg} \quad 2.6$$

The compensating terms appearing in the equations (2.5) and (2.6) are due to the mutual inductance effect. From the above equations power stage model can be deduced and the corresponding model is depicted in Fig.2.2.

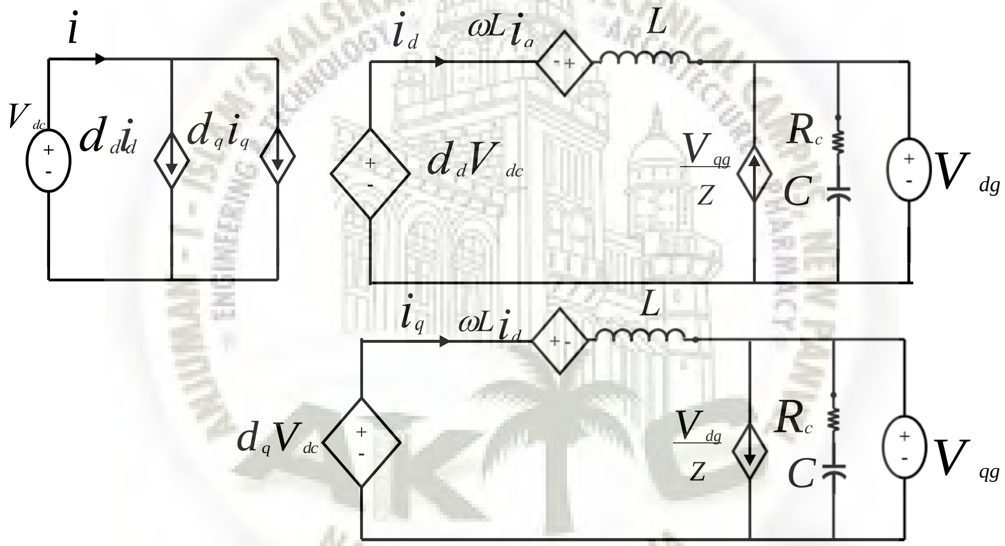


Fig.2.2 Power stage model of three phase grid connected VSI

In Fig.2.2 R_c is the damping resistor used to damp out the oscillations occurring due to the resonance resulted from LC filter. The values of L, C (filter capacitance) and damping resistor R_c have been referred from [14]. Power stage model is helpful in getting a dc operating point so as to design a controller for it. Z is the output impedance given by equation (2.7)

$$Z = \sqrt{\left(R_c{}^2 + \left(\frac{1}{\omega C}\right)^2\right)} \quad 2.7$$

2.1.2 Small Signal Model

The small signal model is then derived from the power stage model similar to 1-Φ inverter modeling by giving a perturbation and then linearizing around an operating point for stable and fast response.

An operating point is defined as follows;

Dc supply voltage= V_{dc}

d-axis duty cycle= D_d

q-axis duty cycle= D_q

d-axis current = I_d

q-axis current = I_q

d-axis grid voltage= V_{dg}

q-axis grid voltage= V_{qg}

For deriving small signal model a perturbation is given around the operating point which is given as follows

$$V_{dc} = V_{dc} + \widehat{v_{dc}}$$

$$D_d = D_d + \widehat{d_d}$$

$$D_q = D_q + \widehat{d_q}$$

$$I_d = I_d + \widehat{i_d}$$

$$I_q = I_q + \widehat{i_q}$$

$$V_{dg} = V_{dg} + \widehat{v_{dg}}$$

$$V_{qg} = V_{qg} + \widehat{v_{qg}}$$

In the above new operating point, parameters with „^" are the small perturbed variables. By adapting these perturbations in equations (2.3), (2.4), (2.5) & (2.6) and neglecting the steady and non-linear terms, equations (2.8), (2.9) and (2.10) can be obtained

$$L\frac{d\widehat{i_d}}{dt} = \widehat{v_{dg}} - D_D\widehat{v_{dg}} - \widehat{d_d}V_{dc} - \omega L i_q \quad 2.8$$

$$C\frac{d\widehat{v_{dg}}}{dt} = \widehat{i_d} + \frac{\widehat{v_{qg}}}{Z} \quad 2.9$$

$$\hat{\imath} = D_d\widehat{i_d} + D_q\widehat{i_q} + \widehat{d_d}I_d + \widehat{d_q}I_q \quad 2.10$$

Based on the above three equations small signal model of grid connected inverter has been derived and shown in Fig.2.3.

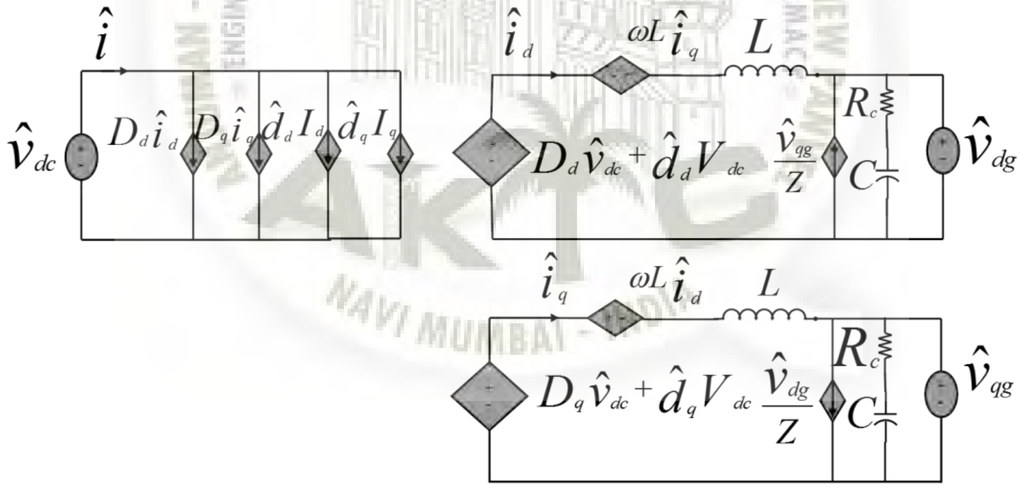


Fig.2.3 Small signal model of three phase grid connected VSI

In the modeled 3-Φ VSI small signal current $\hat{\imath}$ is drawn by VSI from the source $\widehat{vdc}$ which is a function of control signal and its variations and hence it is shown as a dependent source. Due to transformation to synchronous rotating frame (dq) two dependent circuits have been resulted. Both circuits are still cross coupled with each other due to the effect of mutual induction. For the simplicity it is assumed that grid voltage is oriented along d-axis and hence $\widehat{Vqg}$ is considered to be zero.

CHAPTER 3

3.1 Transfer Functions and Bode Plots

The small signal model illustrated in Fig.2.3 is then used to extract open loop transfer functions. The transfer functions of interest are 1. Control function to the filter inductor currents 2.Control function to the grid voltages.

For simplification in deriving transfer functions the grid voltage is oriented along d-axis. So V_{dg} is of constant amplitude as grid voltage is having constant amplitude and V_{qg} =0. From Fig.2.3 concerned transfer functions are derived in frequency domain and are explained as follows

3.1.1 Control to d-axis Current Transfer Function:

This transfer function is obtained from the derived small signal model by assuming $\widehat{Vdc} = 0$.

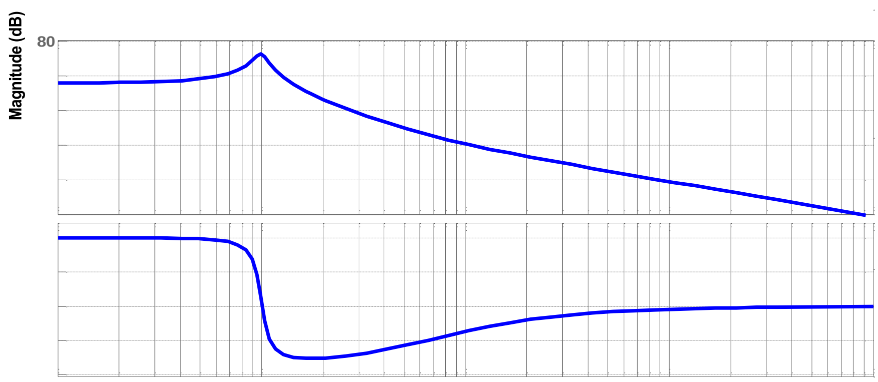
$$\frac{\widehat{i_d}}{\widehat{d_d}} = \frac{V_{dc}}{sL+Z} \tag{3.1}$$

3.1.2 Control to Grid Voltage Transfer Function:

Similarly grid voltage transfer function is developed from the small signal model.

$$\frac{\widehat{v_{dg}}}{\widehat{d_d}} = \frac{V_{dc}Z}{sL+Z} \tag{3.2}$$

Bode plots of control to grid voltage transfer function and control to grid current transfer function is given in Fig.3.1 and Fig.3.2 respectively.



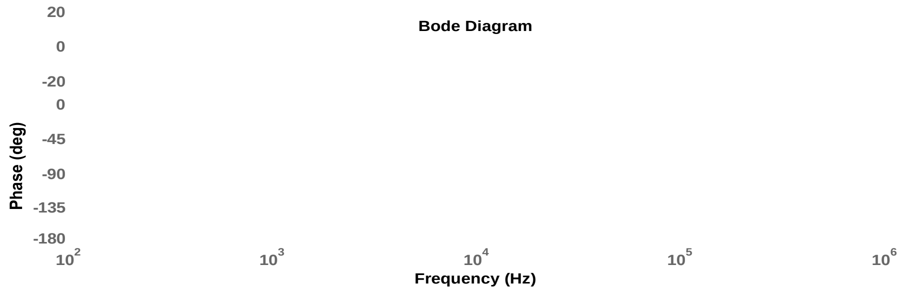


Fig.3.1 Control to grid voltage transfer function bode plot

As LC filter is incorporated between the inverter and grid, it is prone to occurrence of resonance [18]. The resonant frequency is given as follows

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad 3.3$$

In this work resonant frequency f_0 is 993Hz by considering the values of L and C from given in Table.3.1. In Fig.3.1 resonance can be observed i.e at the frequency of 3 Hz there is a phase drop of 45 and at the same time there is a peak in the magnitude plot. However, a suitable damping resistor R_c is used for damping out the oscillations at resonant peak.

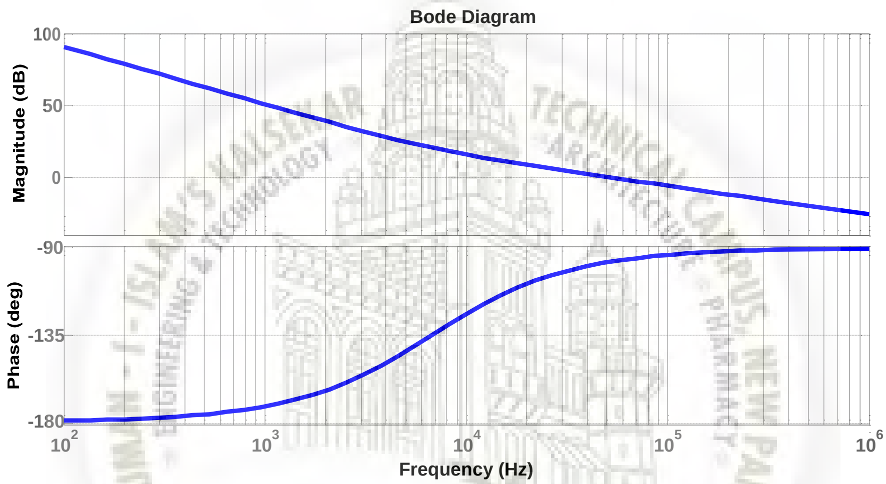


Fig.3.2 Control to grid voltage transfer function bode plot

From Fig.3.2 the phase margin is 80 degree which confirms the stability of the system. The phase cross over frequency is 100Hz and the gain cross over frequency is 10.4 kHz.

Table.3.1

System Parameters (3-Φ)

SL. No.	Parameters	Values
1.	Dc link voltage (V_{dc})	600 Volt
2.	Inverter output frequency (f)	50Hz
3.	Filter inductance (L)	5.46 mH
4.	Filter capacitance(C)	4.7 µF
5.	Damping resistance(R_c)	5 Ω
6.	Dc link capacitance	1800 µF

3.2 Control Strategy for 3-Φ Inverter

The main purpose of control strategy of 3-Φ grid connected inverter is to control the active and reactive power flow independently. Control variable i_d is used for active power control and i_q is used for reactive power control. A control strategy is developed by using equation (3.8). The control algorithm is depicted in Fig.3.3.

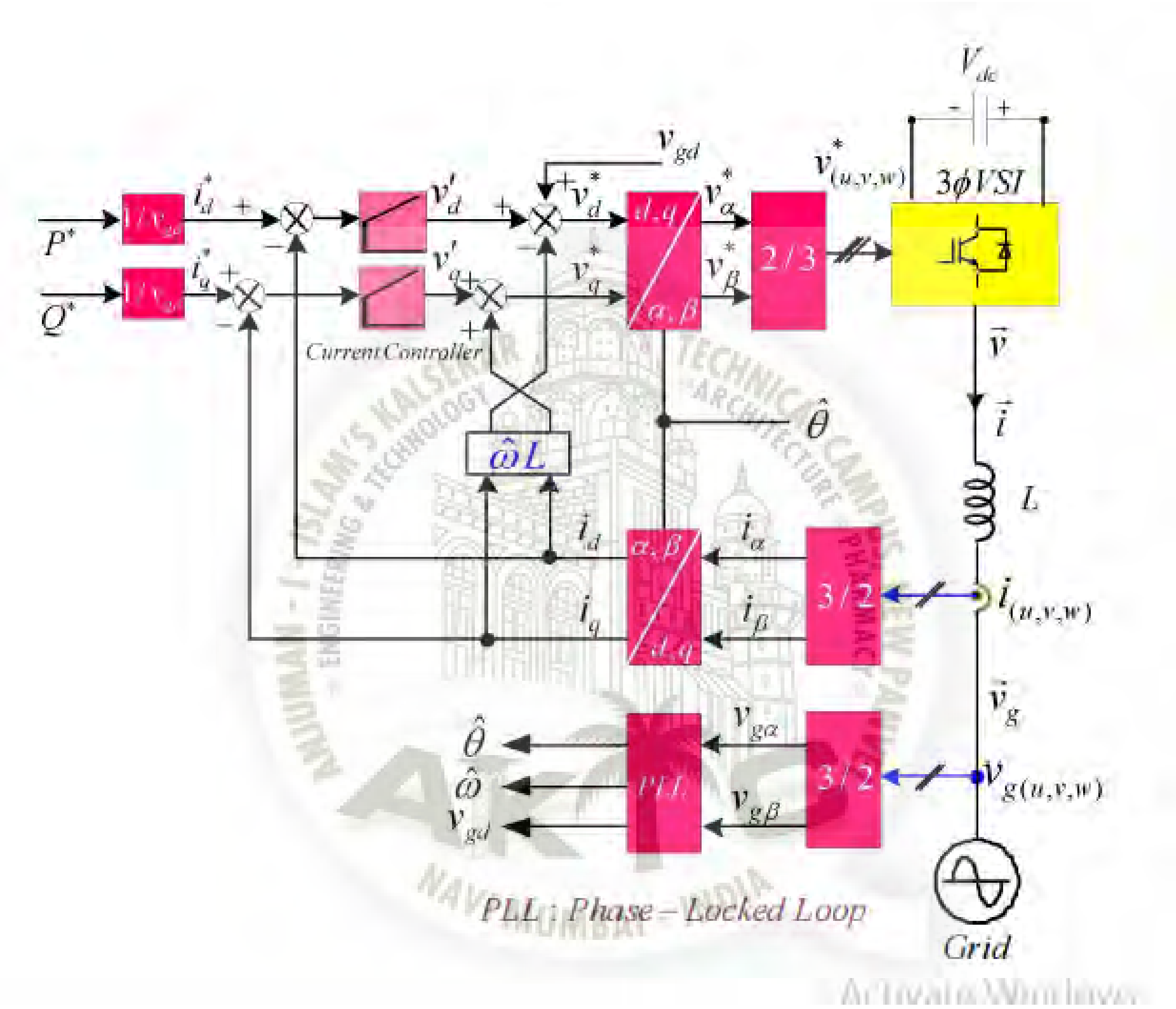


Fig.3.3 Control structure of 3-Φ grid connected VSI

For the transient study and to design a control strategy for controlling the active and reactive power independently transformation of three phase system (abc) to synchronous rotating reference frame is preferred.

Let"s consider the system after the application of Park"s transformation [18] and

V_d = d-axis voltage

V_q= q-axis voltage

I_d= d-axis current

I_q= q-axis current

P= active power

Q= reactive power

S= apparent power

As d-axis and q-axis are of 90 deg phase difference with each other the voltage and current can be expressed as depicted in equation (3.4) and (3.5)

$$V_{dq} = V_d + jV_q \qquad 3.4$$

$$I_{dq} = I_d + jI_q \qquad 3.5$$

It is well known the apparent power

$$S = I_{dq}^{*} V_{dq} \qquad 3.6$$

By substituting values of V_{dq} and I_{dq} from equations (3.4) and (3.5) in equation (3.6), equation (3.7) is derived

$$S = (V_d I_d + V_q I_q) + j(V_q I_d - V_d I_q) \qquad 3.7$$

According to PCC voltage orientation frame V_d is assumed as the maximum value of grid voltage and V_q=0. By substituting this condition in equation (3.7) active power and reactive power are derived as follows

$$P = V_d I_d \qquad 3.8$$

$$Q = -V_d I_q \qquad 3.9$$

The negative sign in the reactive power signifies that it can flow in either direction i.e from inverter to grid and vice versa. For the control algorithm the d-axis reference current is generated from equation (3.8) and also it can be generated from the dc-link voltage error and the q-axis reference current is generated from equation (3.9). So in other words control of d-axis current (I_d) is done for active power control and that of q-axis (I_q) for reactive power control.

CHAPTER 4

4.1 Results

In this section the simulation results are discussed.

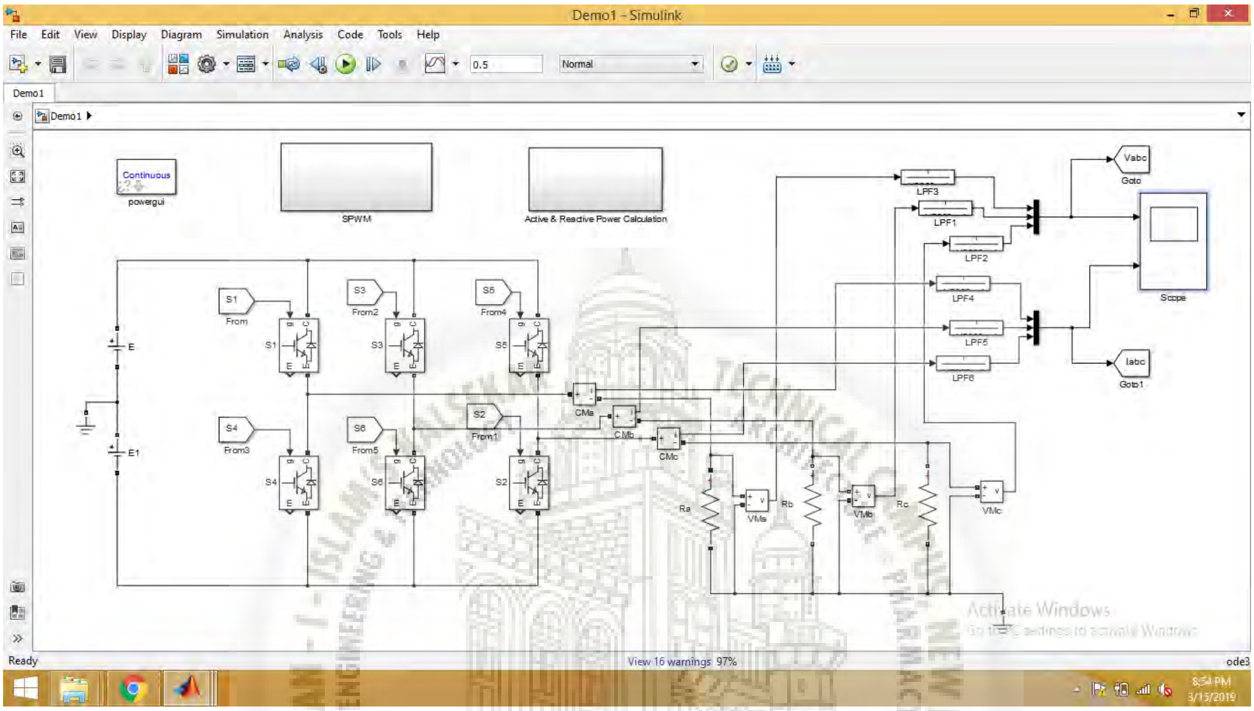


Fig 4.1 Proposed system MATLAB simulation.

Fig 4.1 indicates the proposed **matlab** block diagram simulation. The toolbox used in matlab was **simpower**. The various components used in simulation are IGBT block, resistance, DC voltage source, Voltage measurement, Current measurement, Low pass filter, scope and matlab function. The version of matlab is **MATLAB 2015a.** The two subsystem of proposed structre are to calculate active and reactive power and second one is to implement SPWM block.

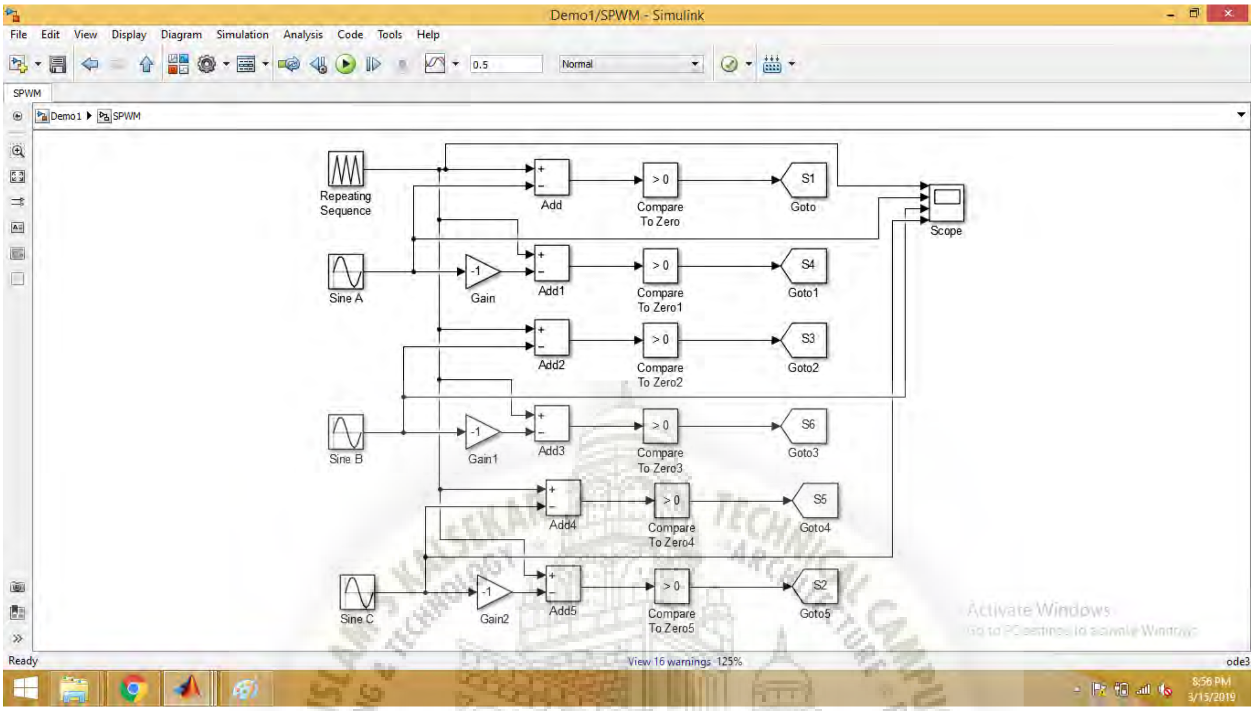


Fig 4.2 SPWM block structure

Fig 4.2 indicates the SPWM block used for the simulation. The triangular carrier wave is compared with sinusoidal wave to obtain the pwm pulse. The frequency of carrier signal is 15kHz. The value is first subtracted from the sine value then is compared with zero. If greater than zero the value is logic 0 . If smaller than zero then value is logic 1. The pulses are then compared and forwarded through **goto** block of matlab to respective switch.

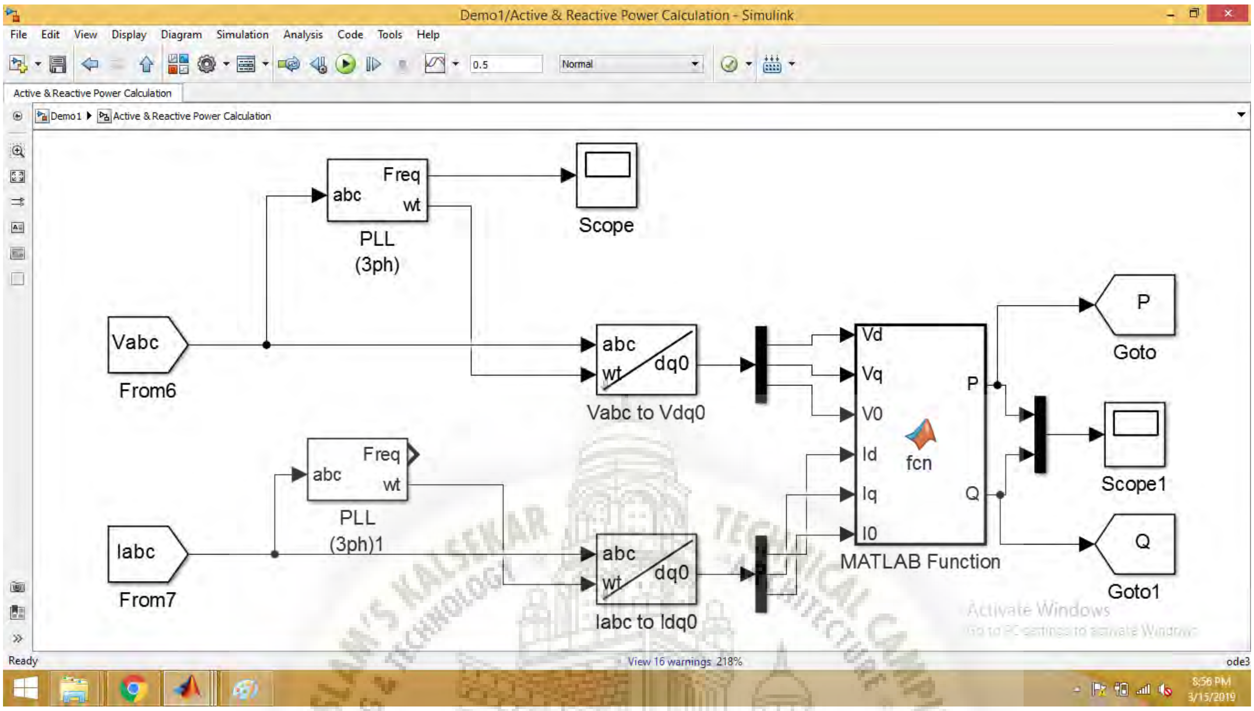


Fig 4.3 Calculation of active and reactive power.

Fig 4.3 represent the active and reactive power calculation block. The voltage measurement and current measurement of output of 3 phase inverter are clubbed into one signal namely Vabc and Iabc. This signal are then passed through **From** block of matlab. First the **PLL** block of matlab is used to calculate frequency and phase of voltage and current signal. This values are then passed through abc to dq transformation block for the calculation of active and reactive power as stated in chapter 2.

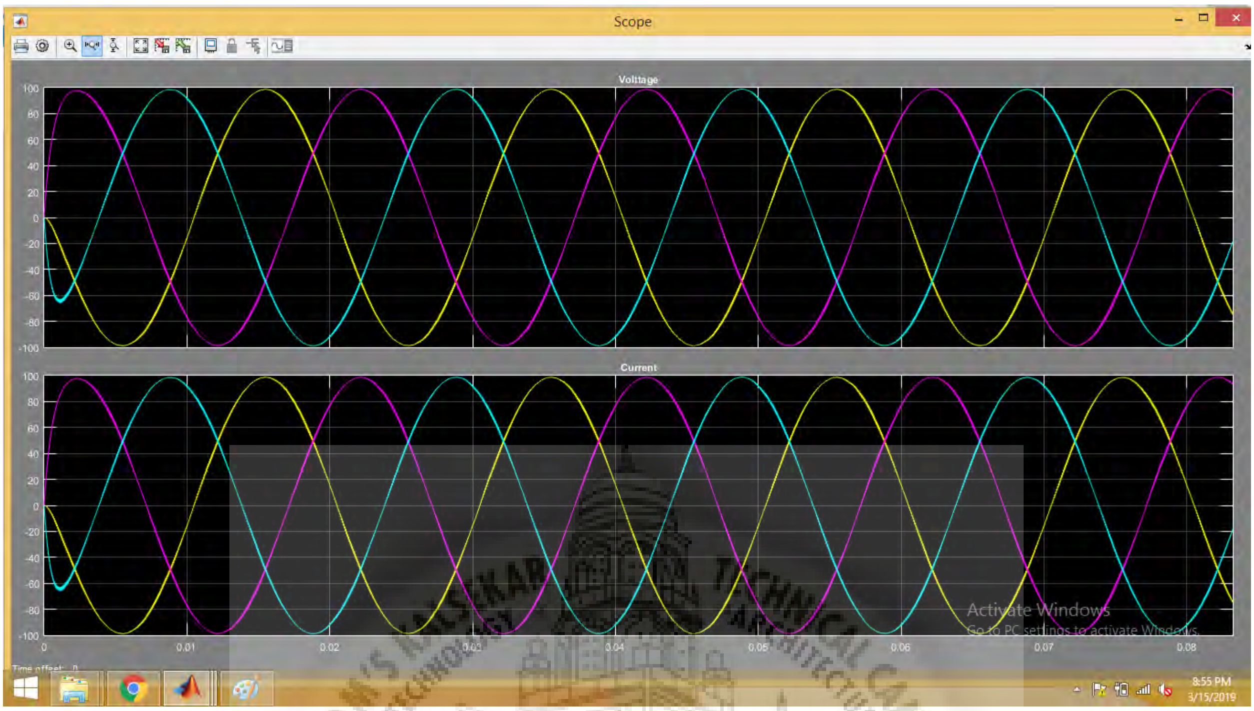


Fig 4.4 Output 3 phase output.

Fig 4.4 represent the 3 phase sinusoidal output. As seen in figure initially the waveform is not sinusoidal due to initial setting. After few time the signal becomes sinusoidal with frequency 50Hz. The waveform is passed through LPF hence the THD of output is very small.

Fig 4.5 Output active and reactive power control.

The fig 4.5 represent the active and reactive power output. The yellow one is active power of value 14325 W. and pink one is reactive power with value approximately zero. The load is resistive hence the reactive power in system is zero.

CHAPTER 5

5.1 Conclusion and Future scope of work

In this thesis a small signal model of a 3-Φ inverter is derived and an average current controller was developed, further bode plots were plotted based on the transfer functions of the derived model. A comparison has been made for the THD% of output voltage with two different type of voltage controllers. In addition to that observation feasibility of the study with theoretical results the modeling was extended to three phase grid connected inverter with LC filter. From the derived small signal model transfer functions were derived and bode plots were plotted to study stability. The effect of resonance was observed from the bode plot of control to output voltage transfer function. A control strategy was developed based on the model and its step responses were plotted. Based on the small signal model of three phase grid connected inverter controller can be developed in order to regulate active and reactive power during grid abnormalities.

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