ROBUST DROOP CONTROLLER FOR ACCURATE PROPORTIONAL LOAD SHARING IN MICROGRID

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DECLARATION CERTIFICATE

This is to certify that the work presented in the thesis entitled "***Robust droop controller for accurate proportional load sharing in microgrid***" submitted by **Anamika, Pankaj Kumar Prasad, Saurabh Raj & Saket Arjun** in partial fulfilment of the requirement of the award of Degree of **Bachelor of Engineering in ELECTRICAL AND ELECTRONICS ENGINEERING** OF Birla Institute of Technology, Ranchi is an authentic work carried out under my supervision and guidance.

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ABSTRACT

DC-AC converters are electronic devices used to change DC direct current (unidirectional current) to alternating current (bi-directional current). Three-phase (3-ϕ) inverter is widely used in power electronics system applications consequently, the DC-AC converters requires a controller with a high degree. Therefore the structure of two parallel three phase inverter with load system has presented. In order to achieve load sharing between parallel inverters, the robust droop control is applied. This control strategy combines frequency and voltage droop method and inverter voltage regulation control scheme. In the external power control structure, the references frequency and magnitude of inverter output voltage are obtained according to the droop characteristics. The improvement of the droop control is made to obtain a more stable voltage and better load sharing between two parallel inverters. The performance of the control strategy is verified in simulation using MATLAB/Simulink.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Distributed generation has attracted people's attention greatly due to its reducing the emission of greenhouse gases, increasing the reliability of the system and alleviating the pressure of power transmission, but output power is affected by the environment, and when there is a fault in the power system, the distributed generation must be quitted which has restricted its application. The Distributed energy resources (DERs) based micro-grid is able to deliver electric power to the grid and able to supply the local loads to ensure reliable power supply of some important and sensitive loads when the grid fails Most of the DER's need power electronics interfaces to be connected to the micro-grid. Consequently, inverters or ac-dc-ac converters are adopted to connect the DER's to the local ac bus with the aim to share loads properly. Distributed generation systems and micro-grids are taking importance when trying to increase the renewable energy penetration. In this sense, the use of intelligent power interfaces between the sources and the grid is mandatory. Usually, in order to inject energy to the grid current-source inverters (CSI) are used, while in standalone or autonomous operation voltage-source inverters (VSI) are used.

Voltage sources inverters are very interesting since they don't need any external reference to stay synchronized, they can operate in parallel with other inverters by using frequency and voltage droops, forming autonomous micro-grids. When these inverters are required to operate in grid-connected mode, they often change its behaviour from voltage to current sources. To achieve flexible micro-grids, which are able to operate in both grid connected and standalone mode. In distributed generation (DG) systems, there may be more than one inverter acting in parallel. Therefore, distributed uninterruptible power supply (UPS) systems as well as the parallel operation of voltage source inverters with other inverters or with the grid, are sensitive to disturbances from the load or other sources and can easily be damaged by over current. Hence, careful attention should be given to system design and the control of parallel operation of inverters. When two or more inverters operate in parallel, the following features must be achieved:

(1) Amplitude, frequency and phase synchronization among the output voltages of inverters,

(2) Proper current distribution according to the capacities,

(3) Flexibility and

(4) Control feature at any time.

The conventional control strategies for the parallel-connected inverters can be classified into two types; active load sharing or current distribution.

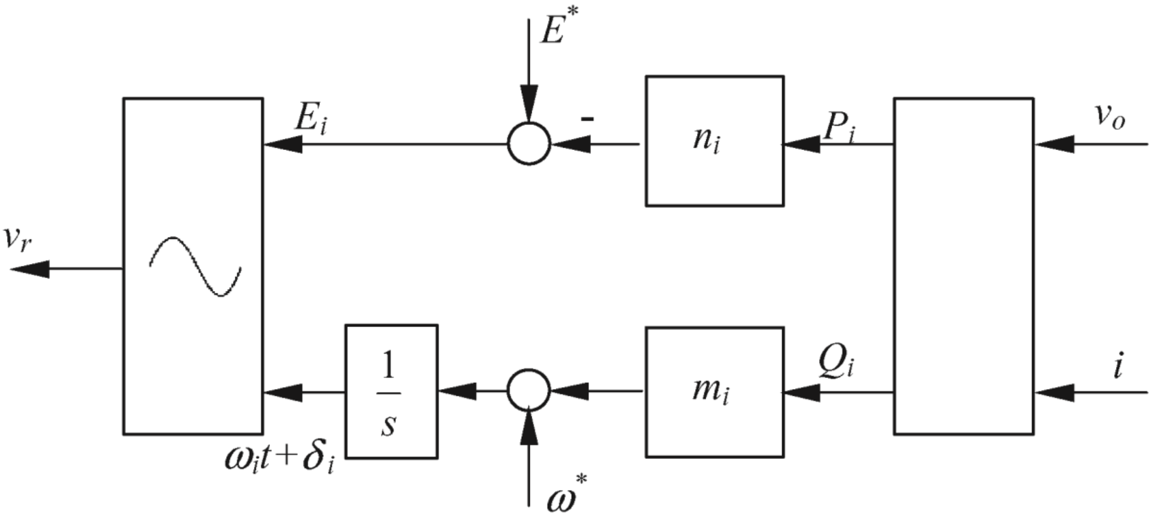

Fig: Conventional Droop Control Scheme

The droop control method for the parallel-connected inverters can avoid the communication mismatch of reference current. It is also defined as wireless control (WC) with no interconnection between the inverters. In this case, the inverters are controlled in such a way that the amplitude and frequency of the reference voltage signal will follow a droop as the load current increases and these droops are used to allow independent inverters to share the load in proportion to their capacities. The main task of this project is to design the control of the parallel inverter system of standalone micro-grid, and the droop control is applied to achieve good load sharing in low voltage micro-grid. Improvement of the droop control is to keep the voltage more stable meanwhile to get a better reactive power sharing the block.

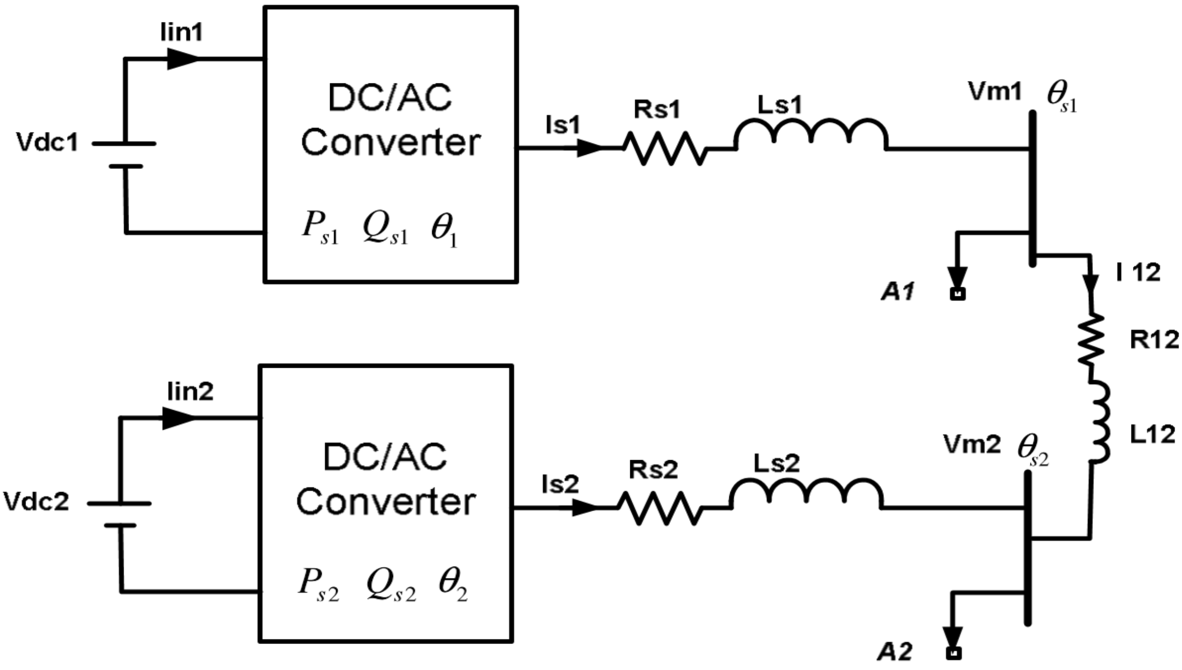

Fig: Schematic diagram of study system

1.2 Problem statement

There is two type to connecting between parallel inverters are wire communication between inverters and droop control. For first type it has disadvantages if one of parallel inverter fail it will effect to the other, the cost of these connecting will be high so the droop control method for the parallel-connected inverters can avoid the communication mismatch of reference current. It is also defined as wireless control (WC) with no interconnection between the inverters. In this case, each inverter has different power and when connecting two parallel inverters to load, the output of voltage of inverter not stable and the inverters did not sharing the load. The inverters need controller to control and make the voltage stable and sharing the current to the load. The droop method controlled inverter by parameters for this control in such a way that the amplitude and frequency of the reference voltage signal will follow a droop as the load current increases and these droops are used to allow independent inverters to share the load in proportion to their capacities.

1.3 Objective

The main objectives of this project are:

1. To design two parallel inverter system of standalone mode.

2. To control two parallel inverters by using droop control method.

3. To control voltage and current for the inverters to load.

1.4 Scope of project

This project is improving droop control for parallel inverters i.e, use of robust droop controller

The scopes of this project are:

1. The parallel inverters with load will be designed in MATLAB.

2. The droop control method to control parallel inverter using MATLAB.

3. To get a better voltage and current output sharing between parallel inverters using MATLAB.

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CHAPTER 2

LITERATURE REVIEW

2.1 Distribution generation

Distribution generations (DG) are electric power generators that produce electricity at a site close to customers or that are tied to an electric distribution system. Distributed generators include, but are not limited to synchronous generators, induction generators, reciprocating engines, micro turbines (combustion turbines that run on high-energy fossil fuels such as oil, propane, natural gas, gasoline or diesel), combustion gas turbines, fuel cells, solar photovoltaic, and wind turbines.

The concept of DG has been recently become commercially extensive. Distributed generation is the interconnection of alternative energy resources to the utility grid system close to the load Point to mitigate the request for and expansion of the electric transmission system. DG is meant to shift the structure of the utility system from a centralized, radial system to energy source connected on the distribution level.

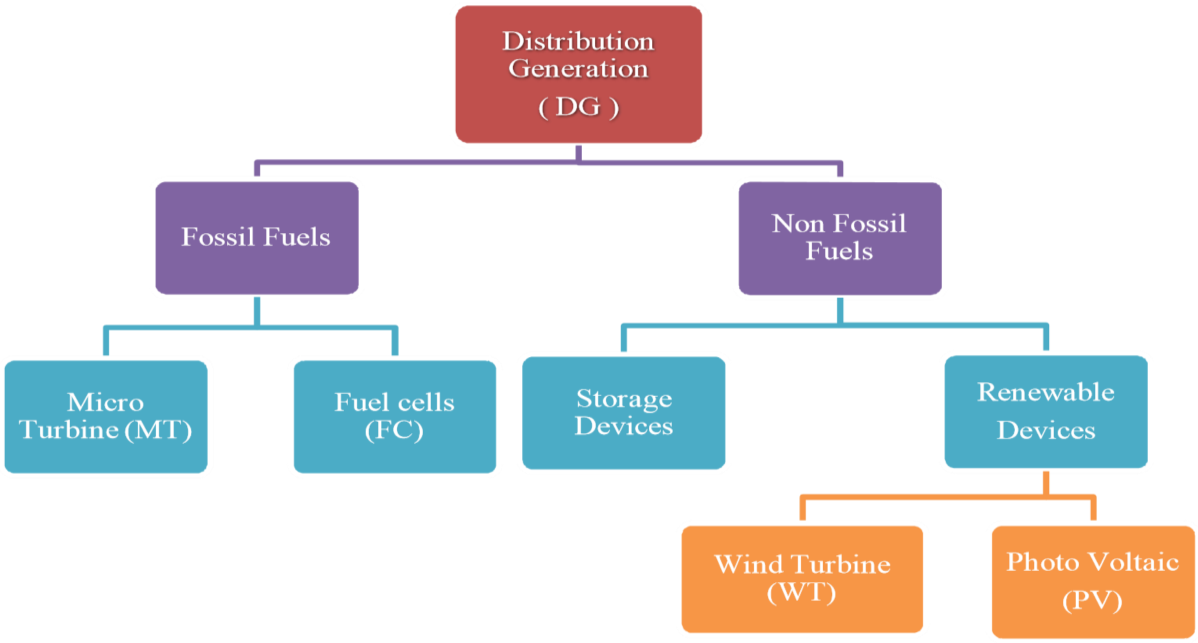

Fig 2.1- Distribution Generation Technology

2.1.1 Benefits of Distributed Generating Systems

Distributed Generation:

- Has a lower capital cost because of the small size of the DG
- May reduce the need for large infrastructure construction because the DG can be constructed at the load location.
- If the DG provides power for local use, it may reduce pressure on distribution and transmission lines.
- With some technologies, produces zero or near-zero pollutant emissions over its useful life.
- With some technologies such as solar or wind, it is a form of renewable energy.

The main advantage of renewable energy systems (RES) is no fossil fuels involved because it is free like sun and wind. This decreases the operational cost of renewable energy systems and reduces operational risks. The major drawback is the initial investment in renewable energy systems, which is often larger than for non-renewable energy sources (RES).

Other disadvantages of RES are the specific requirements of the site and the unpredictability of the power generated. The availability of renewable energy (sun, wind, water) largely determines the feasibility of a renewable energy system and this may raise environmental issues. Figure 2.2 shows renewable energy sources. The unpredictability of RES also means a higher cost for balancing the electricity grid and maintaining reserve capacity e.g. in the event that the wind drops or increases above the operating area of wind turbines. DG and RES have advantages and disadvantages that might be energy-related, grid-related or environmental which need to be evaluated on a case-by-case basis. Most of the distribution energy resources need power electronics interfaces to be connected to the micro-grid. Consequently, inverters are adopted to connect the DERs to the local ac bus with the aim to share loads properly.

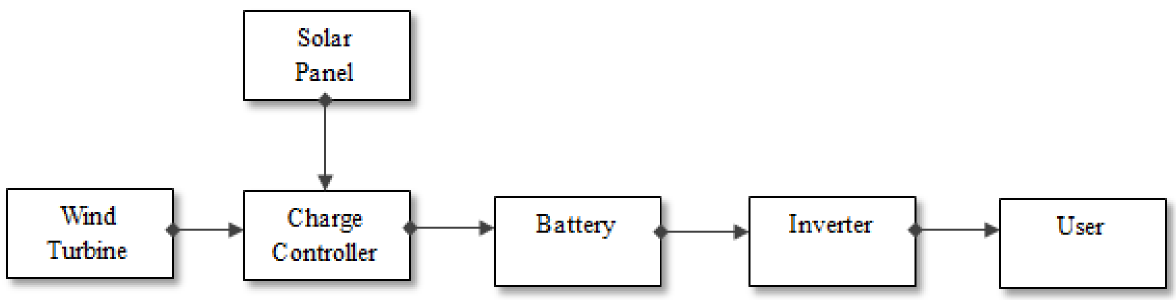

Fig 2.2- Renewable Energy Sources (RES)

2.2 Inverter

Power inverter, or inverter, is an electrical power converter that changes direct current (DC) to alternating current (AC). The converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits.

Solid-state inverters have no moving parts and are used in a wide range of applications, from small switching power supplies in computers, to large electric utility high-voltage direct current applications that transport bulk power. Inverters are commonly used to supply AC power from DC sources such as solar panels or batteries. Figure 2.3 shows the general block diagram.

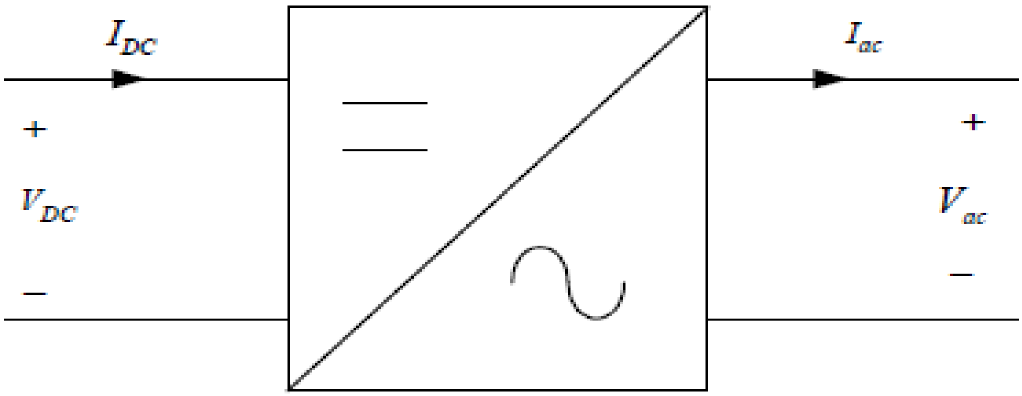

Fig 2.3- General Block Diagram of Inverter

2.2.1 Voltage Source Inverter

The type of inverter that most commonly used is voltage source inverter (VSI) where AC power provides on the output side function as a voltage source. The input DC voltage may be an independent source such as battery, which is called a ’DC link’ inverter. These structure are the most widely used because they naturally behave as voltage source as required by many industrial application, such as adjustable speed drives (ASDs), which are the most popular application of inverters. Figure 2.4 shows the voltage source inverter. Single phase VSIs are used in low range power application where the three phase VSIs is used in medium to high-power application.

The main purposes of three-phase VSIs are to provide a three-phase voltage source, where the amplitude, phase and frequency of the voltage should be controllable.

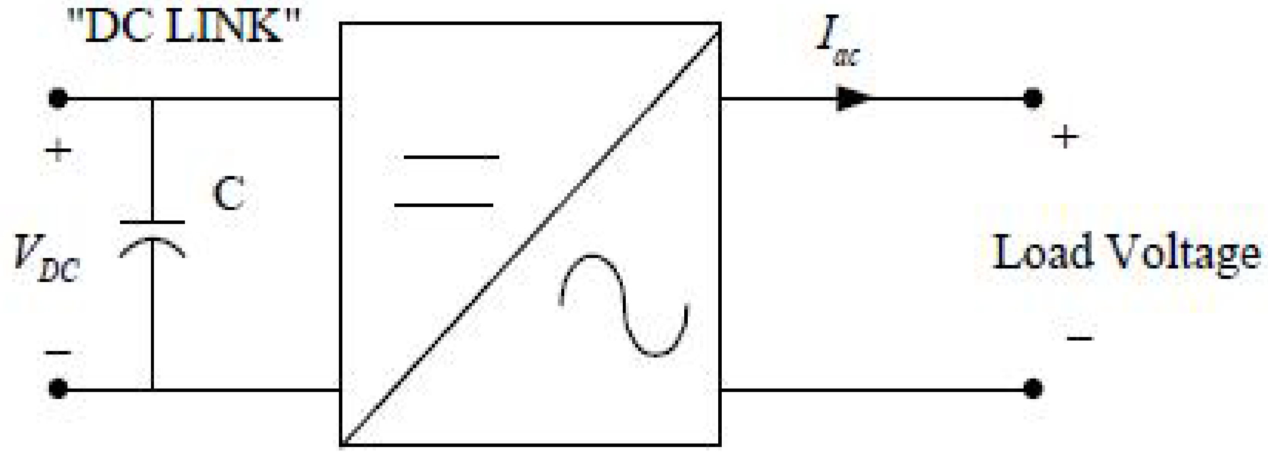

Fig 2.4- Voltage Source Inverter (VSI)

2.2.2 Current Source Inverter

Respectively, CSI the DC source appears as a constant current and the voltage is changing with the load. The protection filter is normally a capacitance in parallel with the DC source. The main advantage of the current source inverter is that it increases the voltage towards the mains itself. Figure 2.5 shows the current source inverter.

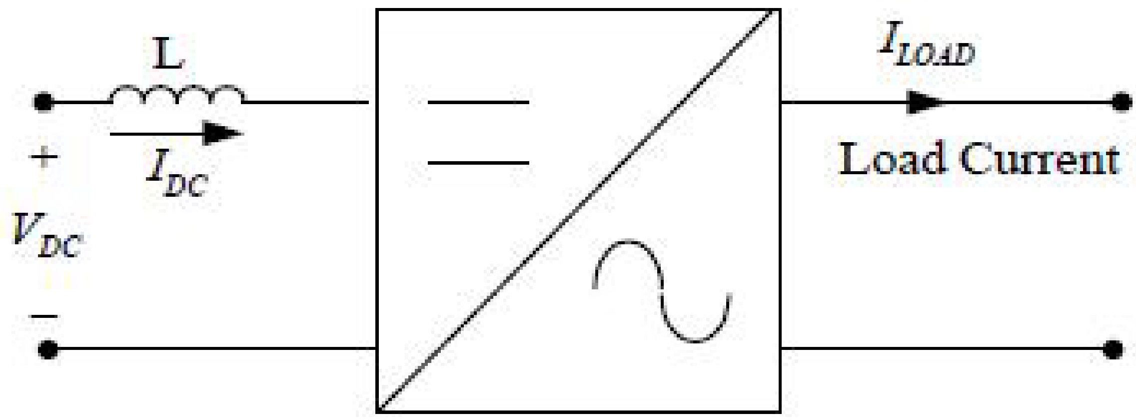

Fig 2.5- Current Source Inverter (CSI)

2.2.3 Three Phase Inverter

Three-phase counterparts of the single-phase half and full bridge voltage source inverters are shown in Figures 2.6 and 2.7. Single-phase VSI cover low-range power applications and three-phase VSI cover medium to high power applications. The main purpose of these topologies is to provide a three-phase voltage source, where the amplitude, phase and frequency of the voltages can be controlled.

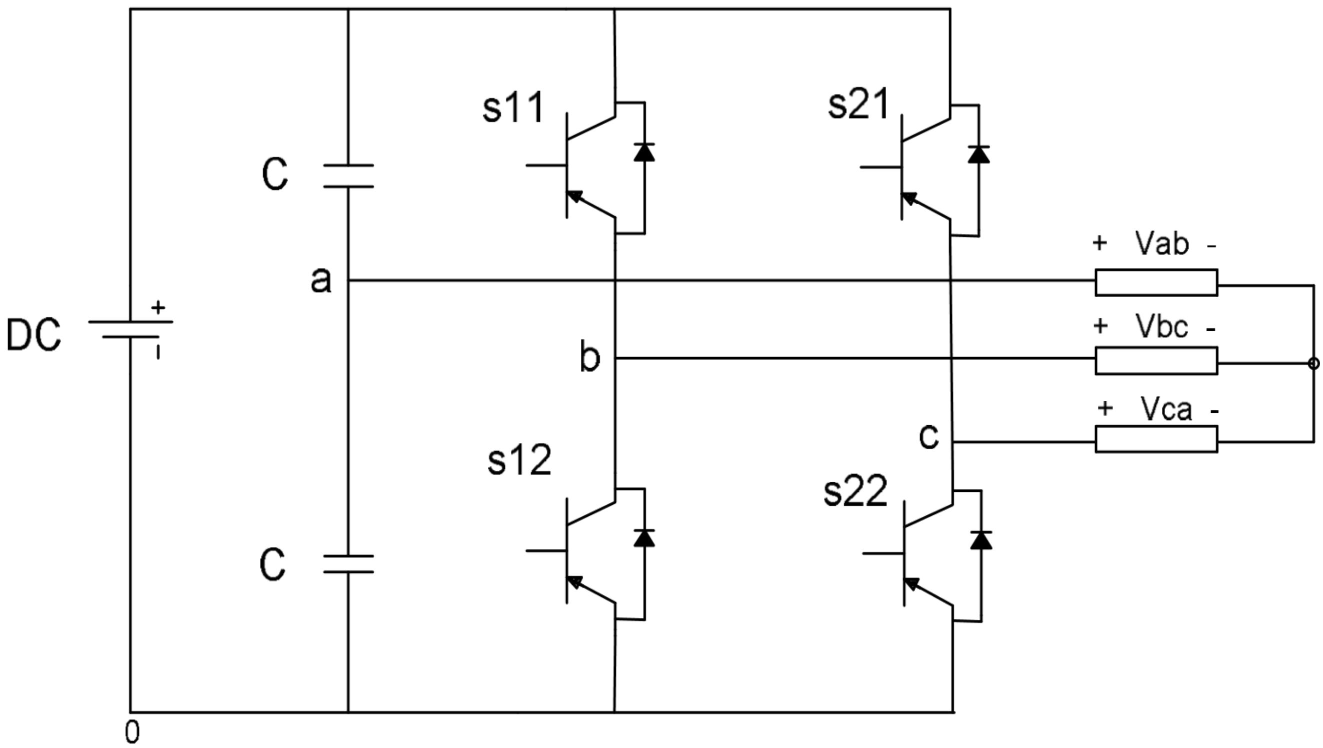

Fig 2.6- Three-Phase Half Bridge Inverter

The three-phase dc/ac voltage source inverters are extensively being used in motor drives, active filters and unified power flow controllers in power systems and uninterrupted power supplies to generate controllable frequency and ac voltage magnitudes using various pulse width modulation (PWM) strategies.

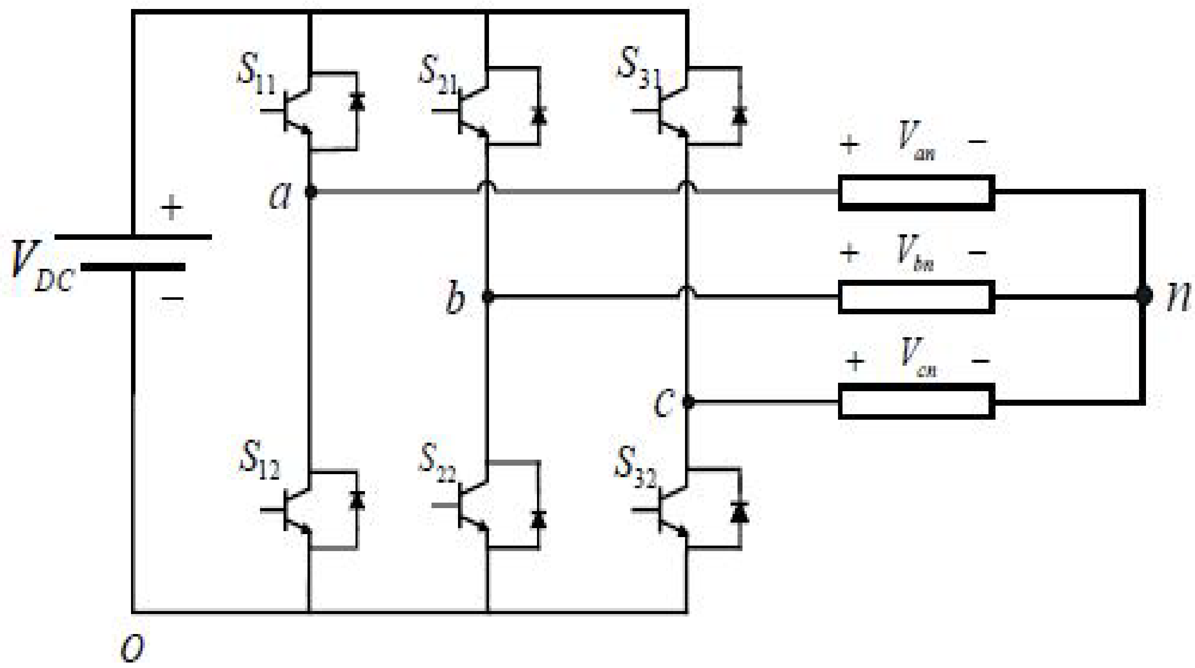

Fig 2.7- Three-phase Full –Bridge Inverter

The input dc is usually obtained from a single-phase or three phase utility power supply through a diode-bridge rectifier and LC or C filter or a DC battery source. We have used a DC battery source in our model.

2.3 Sinusoidal Pulse Width Modulation Technique

- We have used sinusoidal pulse width modulation technique for controlling output voltage of an inverter.
- In this, the width of each pulse is varied in proportion to the amplitude of a sine wave.
- The gating signals are generated by comparing a sinusoidal reference signal with a triangular wave of frequency 'f '.

The frequency of reference signal 'f_r' determines the inverter frequency 'f_o', and its peak amplitude A_r control the modulation index M and in turn the rms output voltage V_0.

∴Modulation Index= A_r/A_c.

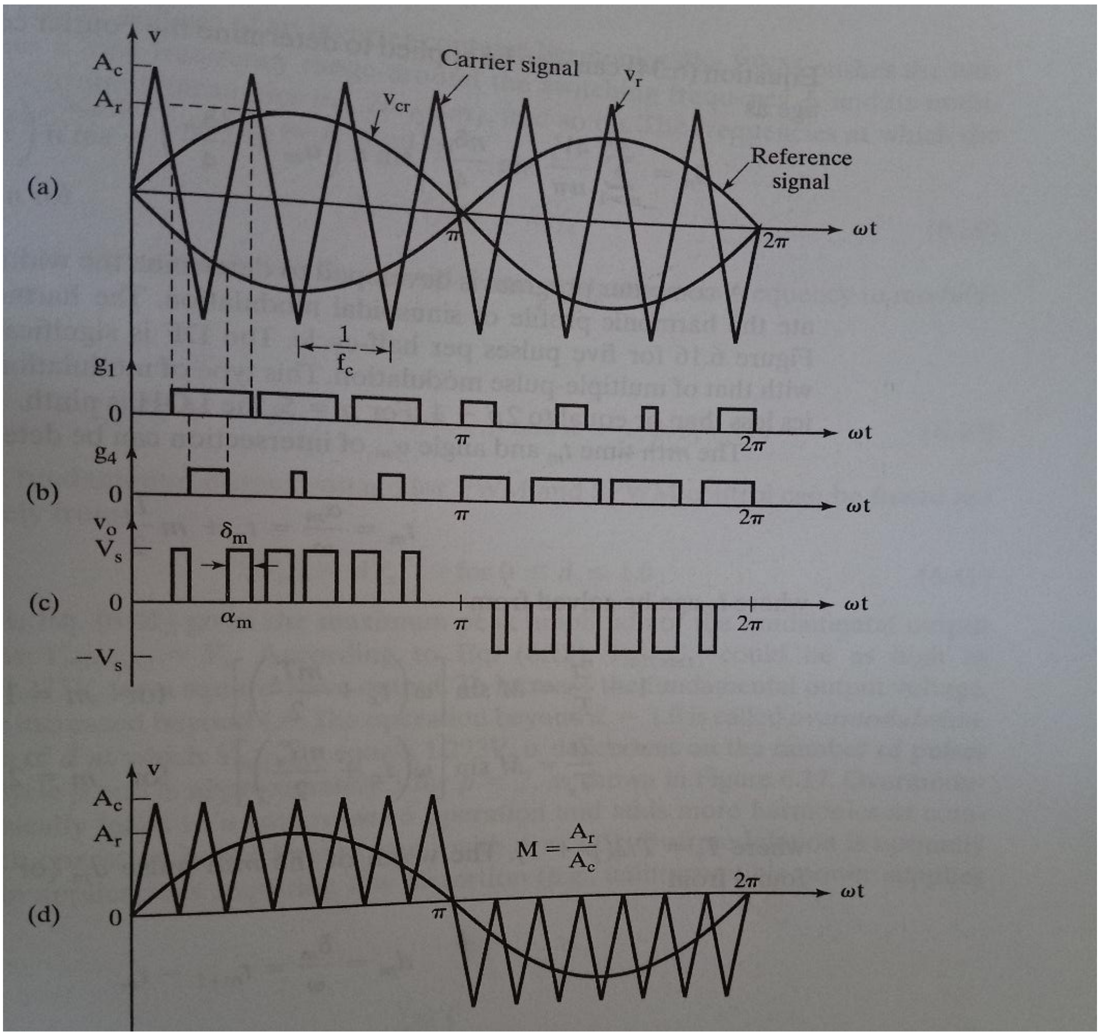

Fig 2.8- Sinusoidal Pulse Width Modulation (SPWM) Technique.

2.4 Control system

A control system is a device or set of devices to manage, command, direct or regulate the behaviour of other devices or systems. A control mechanism is a process used by a control system. There are main controller systems user in the inverter controller such as PI controller, PID controller and droop controller.

2.4.1 PI control

PI controller is proposed is to improve the performance of the soft switched inverter. The duty ratio of the inverter is controlled by PI controller. To provide optimal performance at all operating conditions of the system PI controller is developed to control the duty ratio of the inverter. PI control is a traditional linear control method used in industrial applications. The linear PI controller controllers are usually designed for dc-ac inverter and dc-dc converters using standard frequency response techniques and based on the small signal model of the converter. A Bode plot is used in the design to obtain the desired loop gain, crossover frequency and phase margin. The stability of the system is guaranteed by an adequate phase margin. However, linear PID and PI controllers can only be designed for one nominal operating point. A boost converter’s small signal Model changes when the operating point varies. The poles and a right-half plane zero, as well as the magnitude of the frequency response, are all dependent on the duty cycle. Therefore, it is difficult for the PID controller to respond well to changes in operating point. The PI controller is designed for the boost converter for operation during a start-up transient and steady state respectively.

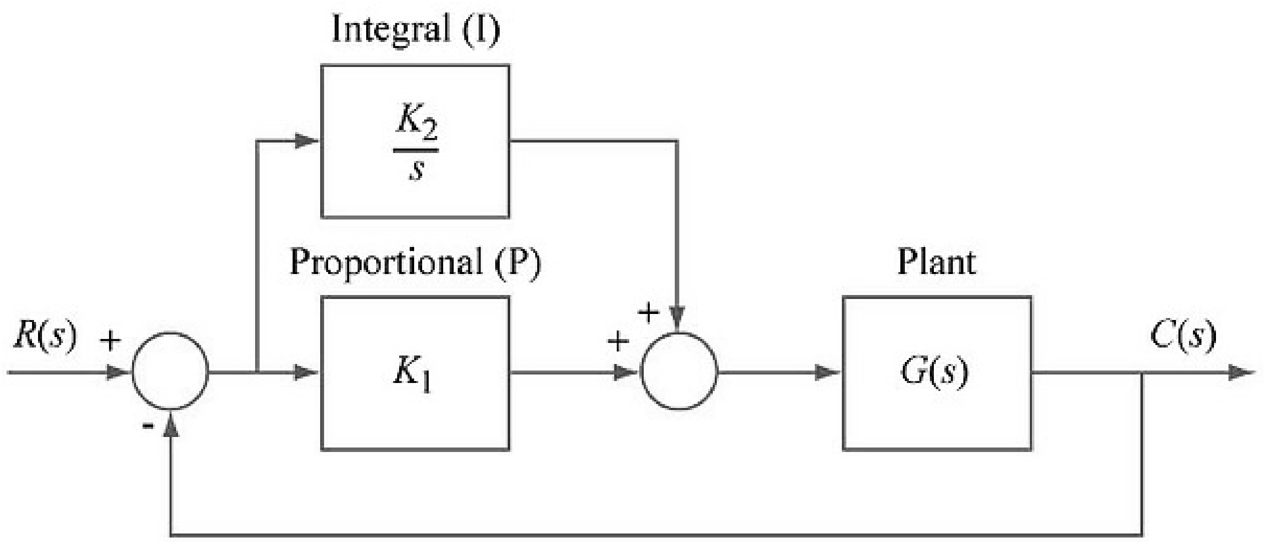

Fig 2.9- Block diagram of PI controller

2.4.2 PID controller

Proportional - integral - derivative controller (PID controller) is a generic control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an "error" value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs. Calculation (algorithm) involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P, I, and D. P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve, a damper, or the power supplied to a heating element. In the absence of knowledge of the underlying process, a PID controller has historically been considered to be the best controller. By tuning the three parameters in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation. Note that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability.

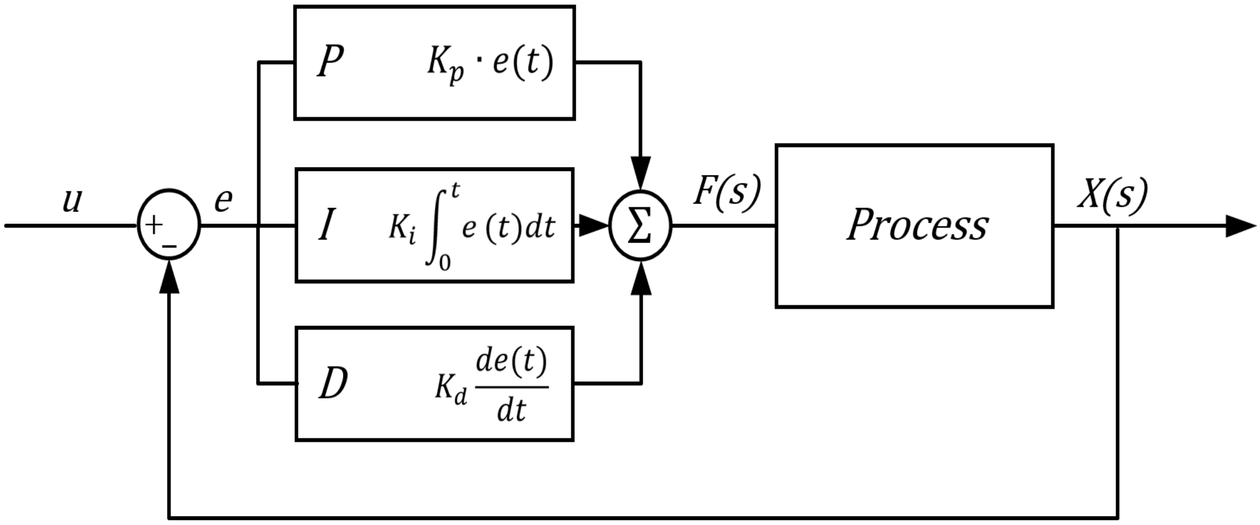

Fig 2.10- Block diagram of PID controller

2.5 Droop control

Droop control strategy is proposed to enhance the dynamic performance of the parallel inverters in micro-grids without communication wire interconnections. A wireless controller is developed by taking the active and reactive current as the control variables, the droop control variables is taken to ensure the power sharing accuracy, and additional terms are added to the droop controller to enhance the dynamic performance.

2.5.1 Review of Droop Control

The droop control method is being used in conventional generators of power plants. In autonomous operation of converter based DG systems, this method can be adopted to share total load and also control voltage magnitude and frequency in a special range.

- We know that

Active power (P) = $\frac{V_1 * V_2}{X}$ **sin δ**

And, **"δ ∝ ωs"** which is again directly proportional to **"f".**

This simply implies that by control in frequency, we can control sharing of "Active power".

- **Reactive power (Q) =** $\frac{V_2}{X}\ (V_1 - V_2 \cos\delta)$; (δ=small).

So, we can say that

Q ∝ ΔV

In this control unit active power of total load can be shared among sources by drooping the frequency as a function of output active power of converter. Output voltage magnitude of the converter against its output reactive power can be drooped to share total load reactive power. As it is shown in (2.1 & 2.2) two coefficients control the slope of change of frequency and voltage against active and reactive power, respectively.

$$\theta_1 = \frac{\omega_1}{p} = \frac{1}{p}(\omega_n - m_p P_{s1}) \qquad \text{......................} \ (2.1)$$

$$V_{m1} = V_n - n_q Q_{s1} \qquad \text{......................} \ (2.2)$$

Where, ω_n and V_n are rated frequency and rated voltage of the system. $m_{p1}, n_{q1},\ P_{s1}$ and Q_{s1} are active power droop coefficient, reactive power droop coefficient, output active power and output reactive power of the converter.

To remove fluctuations and produce an average value of output power, both calculated instantaneous powers passed through a low pass filter with cut of frequency of ω_c that is assumed to be 10% of nominal frequency.

$$\widetilde{P_{s1}} = \frac{3}{2}(V_{qm1}I_{qs1} + V_{dm1}I_{ds1}) \quad \text{……………. (2.3)}$$

$$\widetilde{Q_{s1}} = \frac{3}{2}(V_{qm1}I_{qs1} - V_{dm1}I_{ds1}) \quad \text{…………….. (2.4)}$$

And,

$$P_{s1} = \frac{\omega_c}{p+\omega_c}\widetilde{P_{s1}} = \frac{\omega_c}{p+\omega_c}\frac{3}{2}(V_{qm1}I_{qs1} + V_{dm1}I_{ds1}) \quad \text{……………... (2.5)}$$

$$Q_{s1} = \frac{\omega_c}{p+\omega_c}\widetilde{Q_{s1}} = \frac{\omega_c}{p+\omega_c}\frac{3}{2}\left(V_{qm1}I_{qs1} - V_{dm1}I_{ds1}\right) \text{.. (2.6)}$$

Therefore,

$$pP_{s1} = \frac{3\omega_c}{2}(V_{qm1}I_{qs1} + V_{dm1}I_{ds1}) - \omega_c P_{s1} \quad \text{………..…. (2.7)}$$

$$\mathrm{p}Q_{s1} = \frac{3\omega_c}{2}(V_{qm1}I_{qs1} - V_{dm1}I_{ds1}) - \omega_c Q_{s1} \quad \text{……….. … (2.8)}$$

The outputs of droop control are voltage magnitude and angular frequency which define the reference angle of the load voltage using an integrator. Thus qd axis reference voltage can be determined as follows:

$$V_{qm1}{}^{*} = V_{m1}\cos(\theta_1 - \theta_{s1}) \quad \text{…………….. (2.9)}$$

$$V_{dm1}{}^{*} = -V_{m1}\sin(\theta_1 - \theta_{s1}) \quad \text{……………. (2.10)}$$

Where θ_{s1} comes from PLL.

$$\theta_1 = \omega_n t - \frac{m_p P_{s1}}{p} \quad \text{……………... (2.11)}$$

$$\theta_{s1} = \omega_{s1} t + \theta_{s10} \quad \text{……………… (2.12)}$$

Therefore,

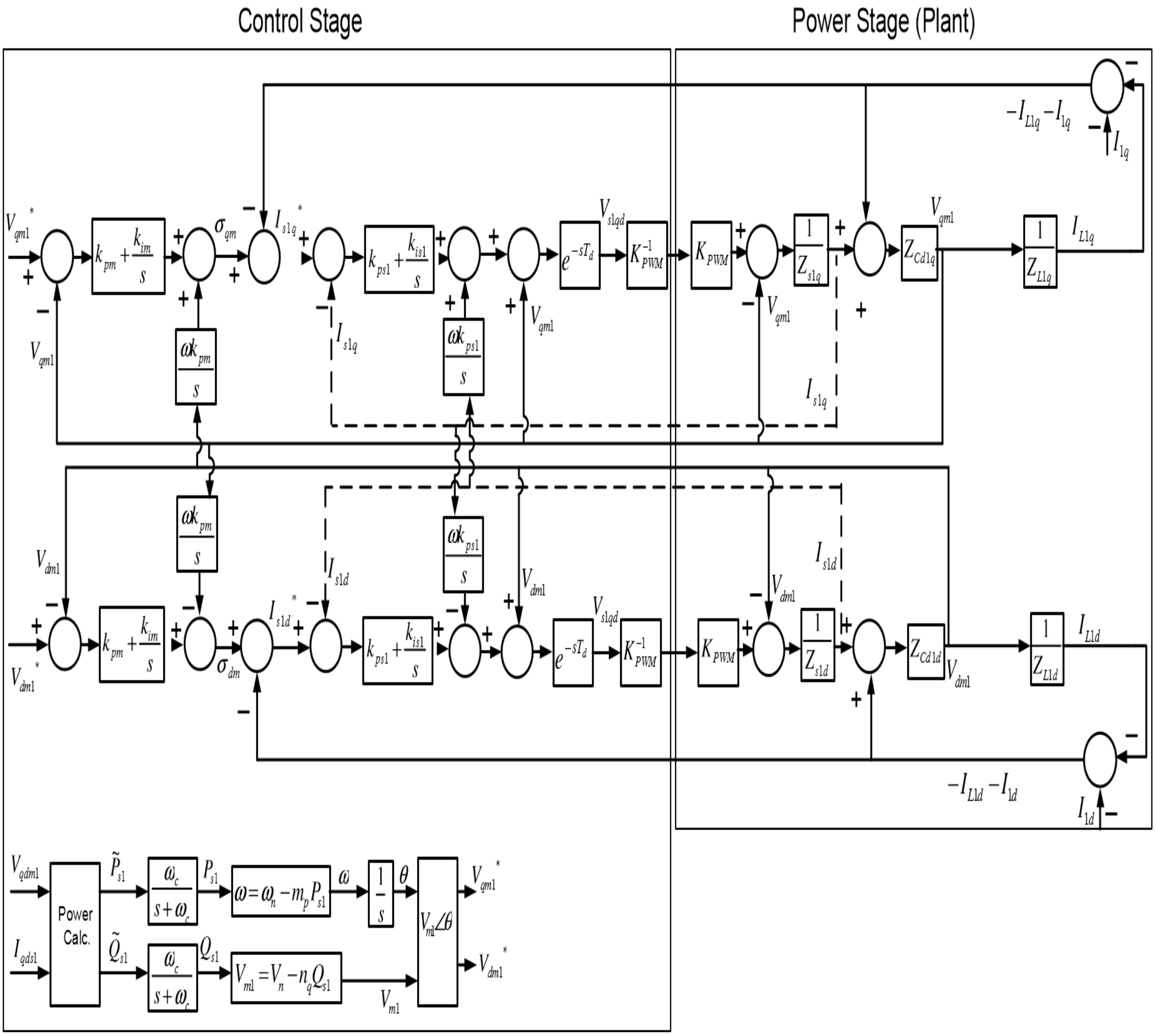

Fig 2.11- Block diagram of controlled unit beside power stage

$$V_{qm1}{}^{*} = (V_n - n_q Q_{s1}) \cos\left((\omega_n - \omega_{s1})t - \frac{m_p P_{s1}}{p} - \theta_{s10}\right) \qquad \ldots\ldots\ldots\ldots (2.13)$$

$$V_{dm1}{}^{*} = -(V_n - n_q Q_{s1}) \sin\left((\omega_n - \omega_{s1})t - \frac{m_p P_{s1}}{p} - \theta_{s10}\right) \qquad \ldots\ldots\ldots\ldots (2.14)$$

2.6 Autonomous Operation of One Converter System

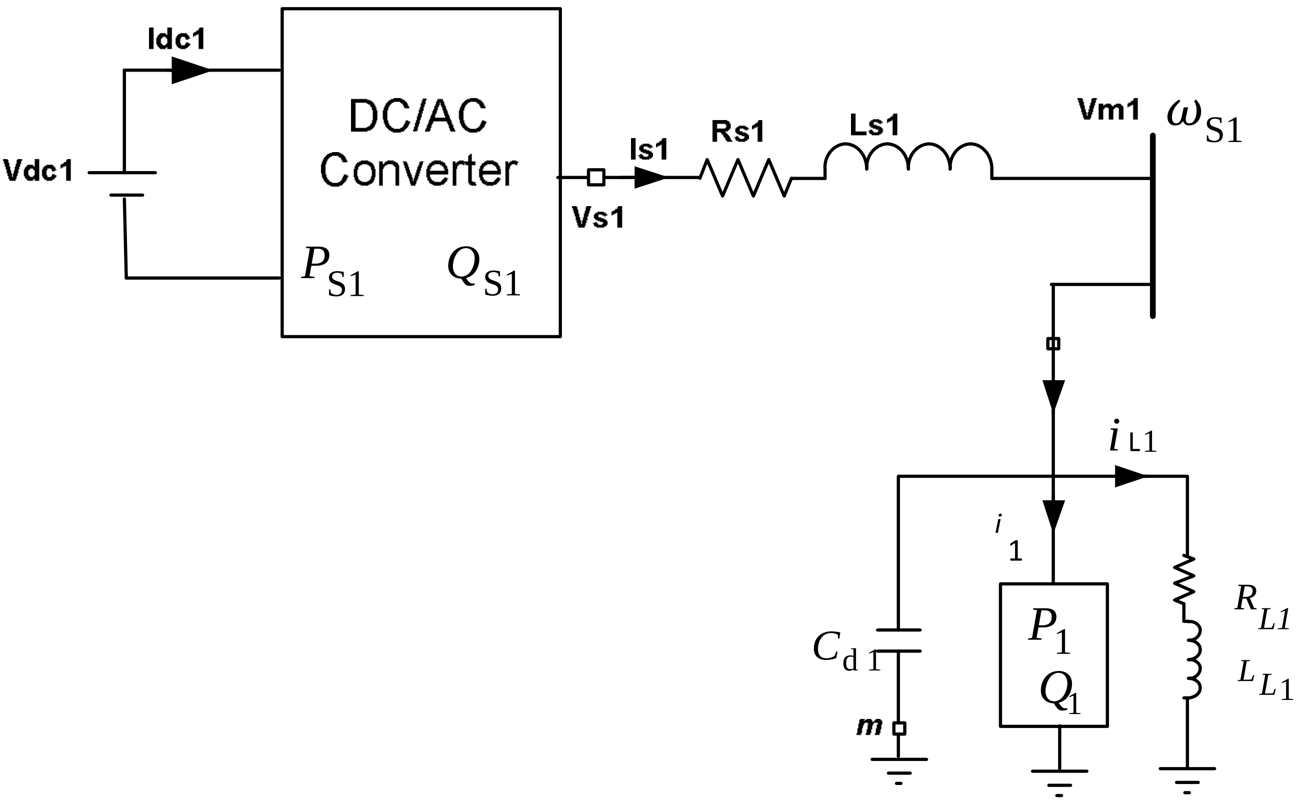

Fig 2.12- Standalone one converter system schematic diagram

Figure 2.1 represents the block diagram of a typical standalone converter base power system. A voltage source converter converts DC input to AC output voltage. A linear RL load and a constant load are connected to the converter through transmission line. A capacitor is connected across the load to smooth its voltage.

The dynamic equations of the system in three phase abc frame are as follows.

Transmission line dynamic equations are:

$$V_{s1a} = V_{m1a} + L_{s1}pI_{s1a} + R_{s1}I_{s1a} \quad \text{……… (2.15)}$$

$$V_{s1a} = V_{m1b} + L_{s1}pI_{s1b} + R_{s1}I_{s1b} \quad \text{………. (2.16)}$$

$$V_{s1a} = V_{m1c} + L_{s1}pI_{s1c} + R_{s1}I_{s1c} \quad \text{……….. (2.17)}$$

The three phase inverter equations are

$$V_{s1a} + V_{n0} = \frac{V_{dc1}}{2}(2s_{ap} - 1) \quad \text{……………... (2.18)}$$

$$V_{s1a} + V_{n0} = \frac{V_{dc1}}{2}(2s_{bp} - 1) \quad \text{……………… (2.19)}$$

$$V_{s1a} + V_{n0} = \frac{V_{dc1}}{2}(2s_{cp} - 1) \quad \text{………………. (2.20)}$$

Where V_{s1abc} , I_{s1abc} and s_{abcp} are output phases voltages, phase currents and switching functions of DG1.

Linear load of DG1 (L1) equations are

$$V_{m1a} = R_{L1}I_{L1a} + L_{L1}pI_{L1a} \quad \text{………………… (2.21)}$$

$$V_{m1b} = R_{L1}I_{L1b} + L_{L1}pI_{L1b} \quad \text{……………….... (2.22)}$$

$$V_{m1c} = R_{L1}I_{L1c} + L_{L1}pI_{L1c} \quad \text{…………………. (2.23)}$$

Where I_{L1abc} are phase current of linear load (L1) of DG1

Capacitor of DG1 equations are

$$C_{d1}pV_{m1a} = I_{s1a} - I_{L1a} - I_{1a} \quad \text{………………… (2.24)}$$

$$C_{d1}pV_{m1b} = I_{s1b} - I_{L1b} - I_{1b} \quad \text{………………… (2.25)}$$

$$C_{d1}pV_{m1c} = I_{s1c} - I_{L1c} - I_{1c} \quad \text{…………………. (2.26)}$$

Where I_{L1abc} are phase current of linear load (L1) of DG1

For converting abc to qdo reference frame the following transformation matrix can be used:

$$\begin{bmatrix} f_q \\ f_d \\ f_0 \end{bmatrix} = K_s \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}, K_s = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix};$$

$\theta = \omega_t + \theta_0$ ………………………………. (2.27)

The inverse transformation matrix is:

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = K_s^{-1} \begin{bmatrix} f_q \\ f_d \\ f_0 \end{bmatrix}; K_s^{-1} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix};$$

……………………………… (2.28)

qd-axis dynamic equations of the system in local frequency reference frame are as follows:

$M_{q1} = M_1 \cos((\omega_1 - \omega_{s1})t + (\theta_{10} - \theta_{s10}))$ ……… (2.29)

$M_{d1} = -M_1 \sin((\omega_1 - \omega_{s1})t + \theta_{10} - \theta_{s10})$ ………. (2.30)

Where ω_1 and θ_{10} are frequency and initial angle of converter.

ω_{s1} and θ_{s10} are instantaneous frequency and initial angle of the system that is measured by a phase locked loop (PLL).

M_1, M_{q1} *and* M_{d1} are modulation index magnitude, q-axis modulation index and d axis modulation index of the converter.

Load voltage equations

$$V_{qm1} = V_{ml}\cos((\omega_{s1} - \omega_{s1})t + (\theta_{s10} - \theta_{s10})) = V_{ml}$$

$$V_{dml} = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.31)}$$

Where V_{ml} is the load voltage magnitude.

$$pI_{s1q} = \frac{1}{L_{s1}}\left(M_{q1}\frac{V_{dc1}}{2} - V_{qm1} - R_{s1}I_{s1q} - L_{s1}I_{s1d}\omega_{s1}\right) \qquad \ldots\text{. (2.32)}$$

$$pI_{s1d} = \frac{1}{L_{s1}}\left(M_{d1}\frac{V_{dc1}}{2} - V_{dm1} - R_{s1}I_{s1d} + L_{s1}I_{s1q}\omega_{s1}\right) \qquad \ldots\text{.. (2.33)}$$

Where I_{s1qd} , R_{s1} and L_{s1} are qd-axis current, resistance and inductance of transmission line p = $\frac{d}{dt}$

Linear load of DG1 (L1) equations are:

$$pI_{L1q} = \frac{1}{L_{L1}}\left(V_{qm1} - R_{L1}I_{L1q} - L_{L1}I_{L1d}\omega_{s1}\right) \qquad \ldots\text{.. (2.34)}$$

$$pI_{L1d} = \frac{1}{L_{L1}}\left(\left(V_{dm1} - R_{L1}I_{L1d} - L_{L1}I_{L1q}\omega_{s1}\right)\right) \qquad \ldots\ldots \text{(2.35)}$$

Where I_{L1qd}, R_{L1} and $L_{L1}$are qd-axis current, resistance and inductance of the linear load.

Capacitor of DG1 equations are:

$$pV_{qm1} = \frac{1}{C_{d1}}\left(I_{s1q} - I_{L1q} - I_{1q} - C_{d1}\omega_{s1}V_{dm1}\right) \qquad \ldots\text{.. (2.36)}$$

$$pV_{dm1} = \frac{1}{C_{d1}}\left(I_{s1d} - I_{L1d} - I_{1d} + C_{d1}\omega_{s1}V_{qm1}\right) \qquad \ldots\text{.. (2.37)}$$

where C_{d1} is the capacitance of parallel capacitor connected to the loads.

****

CHAPTER - 3

METHODOLOGY

3.1 Introduction

In this chapter, it presents the block diagram and the flow chart of this project. Also it will prove the equation for droop controller to share the loading for two parallel inverters.

3.2 Droop control

The analysis will be done for the Q − ω and P − E droop. The sketch of two inverters with resistive output impedances Ro1 and Ro2 operated in parallel is shown in Figure.3.1. The line impedances are omitted because the output impedances of the inverters can be designed to dominate the impedance from the inverter to the ac-bus. The reference voltages of the two inverters are, respectively:

$$v_{r1} = \sqrt{2}E_1 \sin(\omega_1 + \delta_1) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.1)$$

$$v_{r2} = \sqrt{2}E_2 \sin(\omega_2 + \delta_2) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.2)$$

Here, E_1, E_2 are the RMS voltage set-points for the inverters. The power ratings of the inverters are:

$S_1{}^* = E^* I_1{}^*$ and $S_2{}^* = E^* I_2{}^*$.

They share the same load voltage.

$$v_0 = v_{r1} - R_{o1} i_1 = v_{r2} - R_{o2} i_2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.3)$$

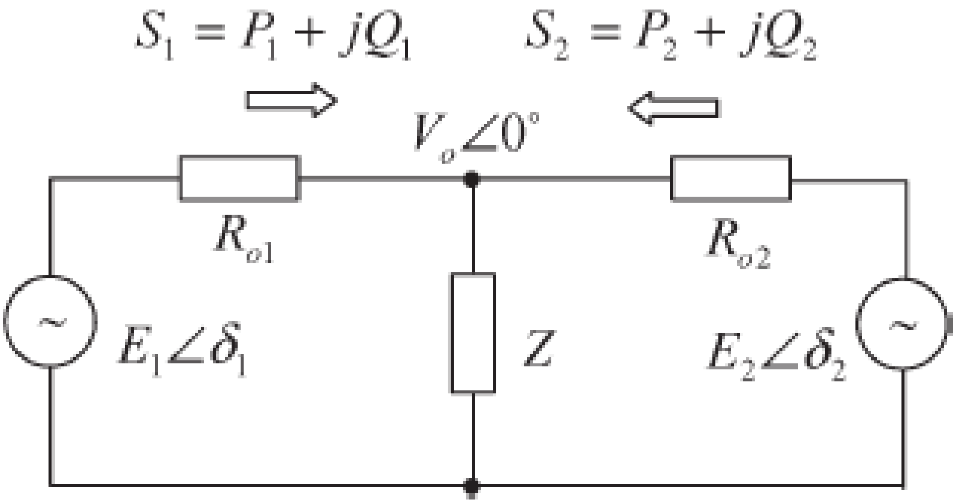

Fig 3.1- Two inverters with resistive output impedances operated in parallel

The active and reactive powers of each inverter injected into the bus are

$$P_i = \frac{E_i V_o \cos\partial_i - V_o{}^2}{R_{oi}} \quad \text{……………………………} (3.4)$$

$$Q_i = -\frac{E_i V_o}{R_{oi}} \sin\partial_i \quad \text{……………………………} (3.5)$$

To share the loads of order the inverter, the normal droop controller

$$E_i = E^* - n_i P_i \quad \text{…………………………….. } (3.6)$$

$$\omega_{i=}\omega^* + m_i Q_i \quad \text{…………………………….. } (3.7)$$

As shown in Figure. 3.2, is widely used to generate the amplitude and frequency of the voltage reference V_{ri} for Inverter i , where ω∗ is the rated frequency.
Note that, from equation (3.5), the reactive power Qi is proportional to -∂_i for a small power angle (∂_i) in order to make sure that the Q-ω loop is a negative feedback loop so that it is able to regulate the frequency, the sign before $m_i Q_i$ in equation (3.7) is positive, which makes it a boost term. The droop coefficients n_i and m_i are normally determined by the desired voltage drop ratio $n_i P_i{}^* / E^*$ and frequency boost ratio $m_i Q_i{}^* / \omega^*$ respectively, at the rated real power

P^* and reactive power Q^*. The frequency ω_i is integrated to form the phase of the voltage reference v_{ri}.

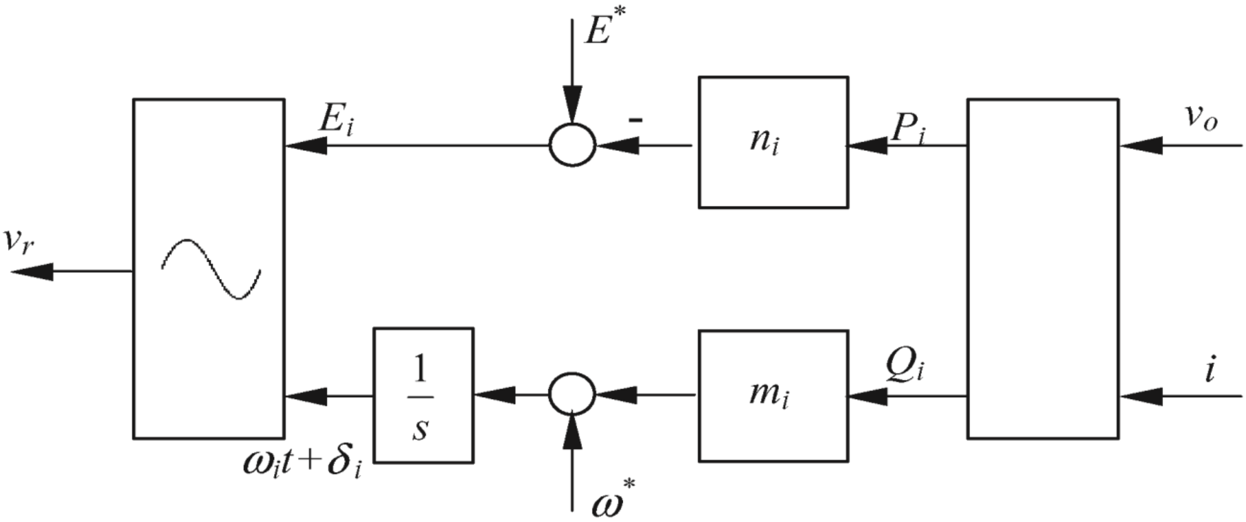

Fig 3.2- Conventional droop control scheme

In order for the inverters to share the load in proportion to their power ratings, the droop coefficients of the inverters should be in inverse proportion to their power ratings.

i.e., n_i and m_i should be chosen to satisfy

$$n_1 S_1{}^* = n_2 S_2{}^* \quad \text{……………………………… (3.8)}$$

$$m_1 S_1{}^* = m_2 S_2{}^* \quad \text{……………………………… (3.9)}$$

It is easy to see that n_i and m_i also satisfy

$$\frac{n_1}{m_1} = \frac{n_2}{m_2}$$

- Per unit output impedances of all inverters operated in parallel should be the same in order to achieve accurate proportional real power sharing for conventional droop control scheme.

3.3. ROBUST DROOP CONTROLLER TO ACHIEVE ACCURATE PROPORTIONAL LOAD SHARING

3.3.1Proposed Control Strategy

As a matter of fact, the voltage droop (3.6) can be re-written as

$\Delta E_i = E_i - E^* = -n_i P_i$ …………………… (3.10)

and the voltage E_i can be implemented via integrating ΔE_i, that is

$E_i = \int_0^t \Delta E_i \, dt$ ………………….. (3.11)

This works for the grid-connected mode where is ΔE_i is eventually zero (so that the desired power is sent to the grid as in proposed scheme.

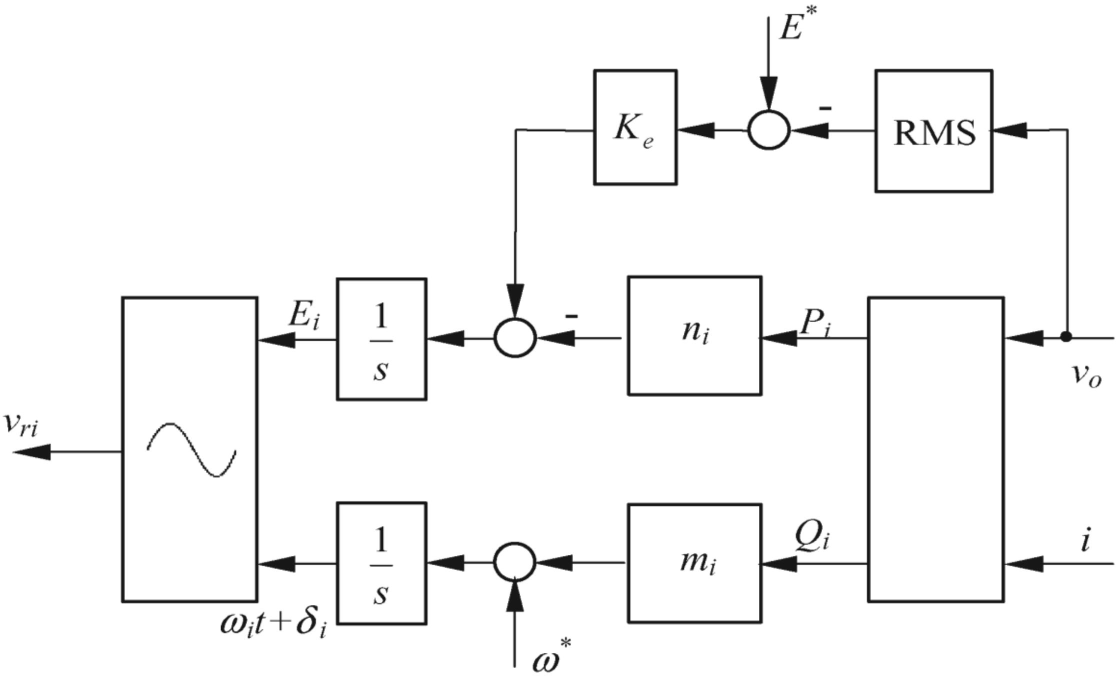

Fig 3.3 – Proposed robust droop controller to achieve accurate proportional load sharing

However it does not work for the standalone mode because the actual power P_i is determined by the load and ΔE_i cannot be zero. This is why different controllers had to be used for the standalone mode and the grid-connected mode, respectively. When the operation mode changes, the controller needs to be changed as well. It would be advantageous if the change of controller could be avoided when the operation mode changes.

Another issue is that, according to (3.1), the load voltage V_o drops when the load increases. The voltage also drops due to the droop control, according to (3.6). The smaller the coefficient n_i, the smaller the voltage drop. However, the coefficient m_i, needs to be big to obtain a fast response. In order to make sure that the voltage remains within a certain required range, the load voltage drop $E^* - V_o$ needs to be fed back in a certain way, according to the basic principles of control theory. It can be added to ΔE_i via an amplifier K_e. This actually results in an improved droop controller shown in Fig. 3.3. This strategy is able to eliminate (at least considerably reduce) the impact of computational errors, noises and disturbances. As to be explained below, it is also able to maintain accurate proportional load sharing and hence robust with respect to parameter drifts, component mismatches and disturbances.

In the steady state, the input to the integrator should be zero.

Hence,

$$n_i P_i = K_e(E^* - V_o) \qquad \text{.................................. (3.12)}$$

The right-hand side of the above equation is always the same for all inverters operated in parallel as long as K_e is chosen the same, which can be easily met. Hence

$$n_i P_i = constant$$

Which guarantees accurate real power sharing without having the same E_i. This is more natural than the case with the conventional droop controller. The accuracy of real power sharing no longer depends on the inverter output impedances (including the feeder impedance) and is also immune to numerical computational errors and disturbances.

The only possible error in the real power sharing comes from the error in measuring the RMS value of the load voltage. From (3.12) the real power deviation ΔP_i due to the error ΔV_{oi} in the measurement of the RMS voltage is

$$\Delta P_i = \frac{-K_e}{n_i} \Delta V_{oi} \qquad \text{.................. (3.13)}$$

For two inverters operated in parallel with

P_1+P_2 = $P_1{}^*$+ $P_2{}^*$, the relative real power sharing error due to the error in the measurement of the RMS voltage

ΔV_o = ΔV_{o2} -ΔV_{o1} is

$$e_p\% = \frac{P_1}{P_1{}^*} - \frac{P_2}{P_2{}^*} = \frac{\Delta P_1}{P_1{}^*} - \frac{\Delta P_2}{P_2{}^*} = \frac{K_e E^*}{n_i P_i}\,\frac{\Delta V_o}{E^*}$$

This characterizes the percentage error $e_p\%$ of the real power sharing with respect to the percentage error $\frac{\Delta V_o}{E^*}$ of the RMS voltage measurement. The term $\frac{K_e E^*}{n_i P_i}$ is the inverse of the voltage drop ratio with respect to the rated voltage the rated power. If all inverters measure the voltage at the same point accurately, then the error ΔV_o can be made zero and exact proportional sharing can be achieved.

The strategy also reduces the load voltage drop. From (3.12), the load voltage is

$$V_o = E^* - \frac{n_i}{K_e} P_i = E^* \frac{n_i P_i}{K_e E^*} E^*$$

where $\frac{n_i P_i}{K_e E^*} E^*$ is the voltage drop ratio. Note that the voltage drop ratio here is the overall effective voltage drop ratio, which is much smaller than the drop ratio due to the droop effect and/or the load effect, but the one in both the conventional droop controller and the controller in model is just the voltage drop ratio due to the droop effect and does not include the voltage drop ratio due to the load effect. Although the controller can compensate the voltage drop due to the load effect, it cannot compensate the voltage drop due to the droop effect. The proposed strategy can compensate the voltage drop due to both effects and, hence, offers much better capability of voltage regulation. The voltage drop here is no longer determined by the output impedance originally designed as characterized in, but by the parameters n_i, K_e and the actual power Pi. It can be considerably reduced by using a large K_e. If there are errors in the RMS voltage measurement the trade-off between the voltage drop and the accuracy of power sharing has to be made because the voltage drop is proportional to n_i / K_e but the sharing error is inverse proportional to n_i / K_e. Here, is a calculation example. Assume that the voltage drop ratio at the rated power is $n_i P_i / K_e E^*$= 10% and the error in the RMS voltage measurement is $\Delta V_o / E^*$ =

0.5%, whether because the local voltages of inverters are measured or because the sensors are not accurate. Then, the error in the real power sharing is $K_e E^*/(n_i {S_1}^*)(\ \Delta V_o/E^*)$ = 0.5%/10% = 5%, which is reasonable.

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CHAPTER 4

RESULTS AND ANALYSIS

4.1 Introduction

The above strategy has been verified on MATLAB/Simulink software, which consists of a three- phase inverter.

The circuit diagram of inverter is shown in Fig. 4.1. The inverters are connected to the ac bus via a circuit breaker *CB* and the load is assumed to be connected to the ac bus. The values of the resistor and inductors are 10 Ω and 0.0497H, respectively. The frequency of the system is 50 Hz. The input DC source voltage is 120 V.

The modulation index for the inverter designing is 0.5.

So, the reference signal for the Sinusoidal Pulse Width Modulation (SPWM) is 0.5 sin (314.15t).

The output active power of the inverter is 4500 watts and the reactive power is 500VAR as shown in Fig 4.2(a) & (b).

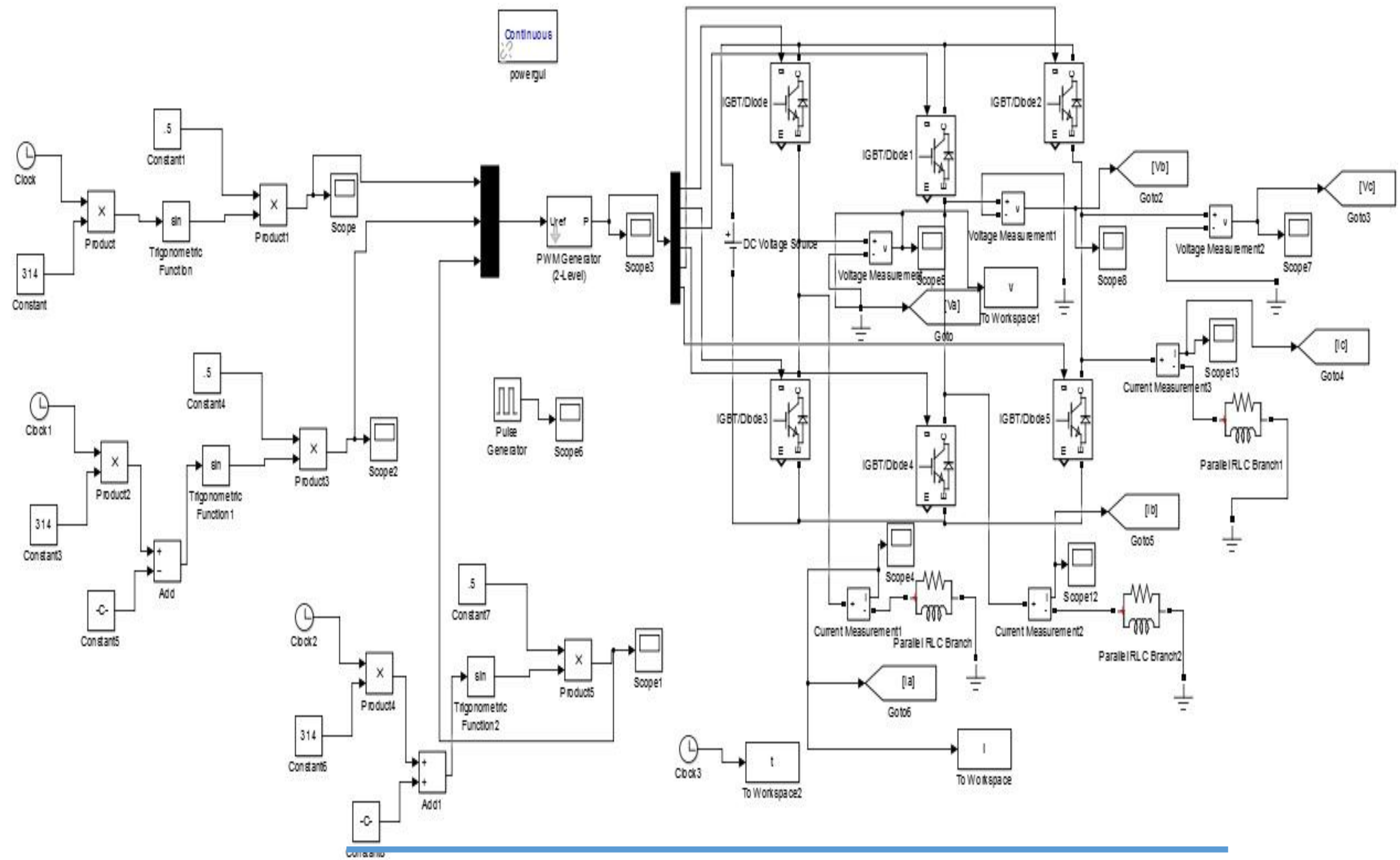

Fig4.1- Model of 3-phase inverter on Simulink

4.2 Experimental Outputs

4.2.1. Voltage waveform of Inverter

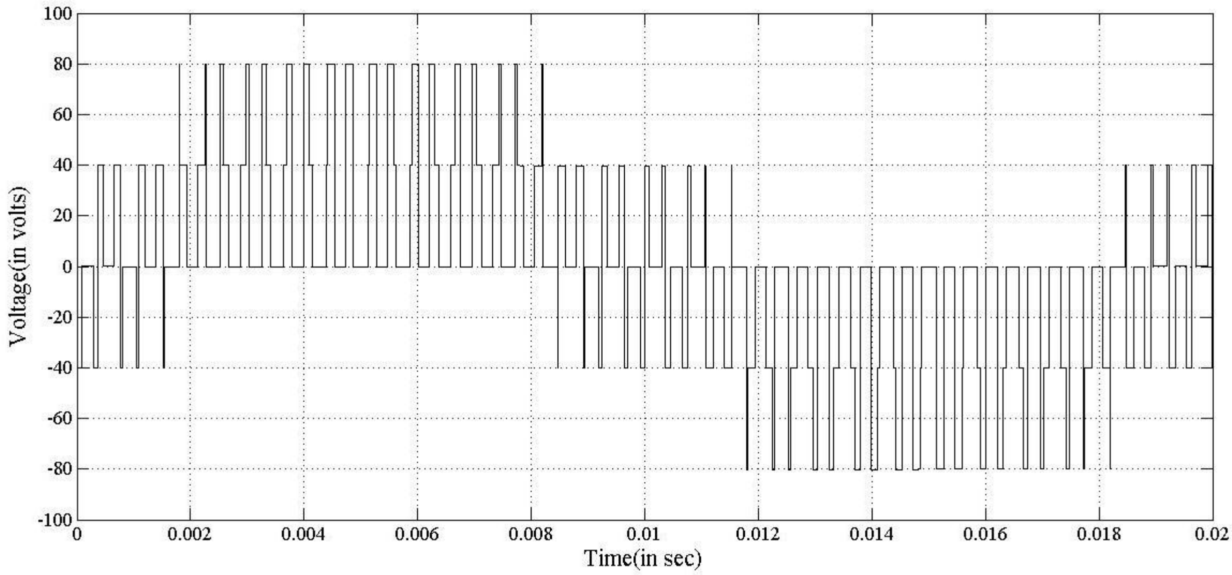

Fig 4.2(a) - Voltage waveform of Inverter

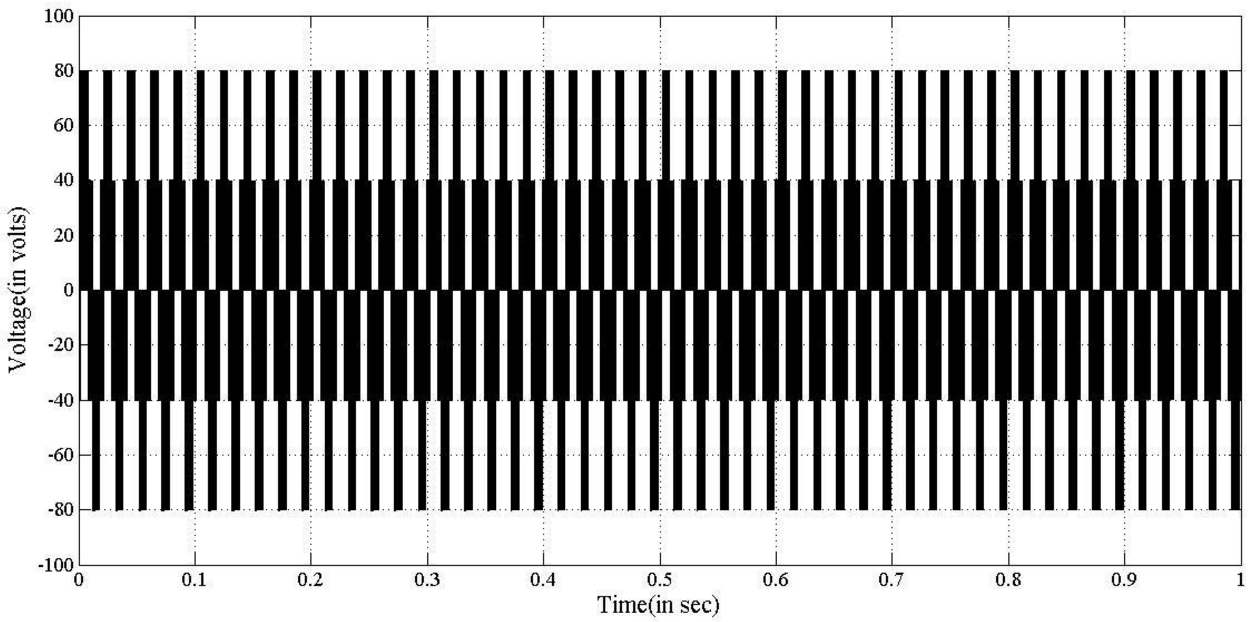

Fig 4.2(b) – Voltage waveform of Inverter

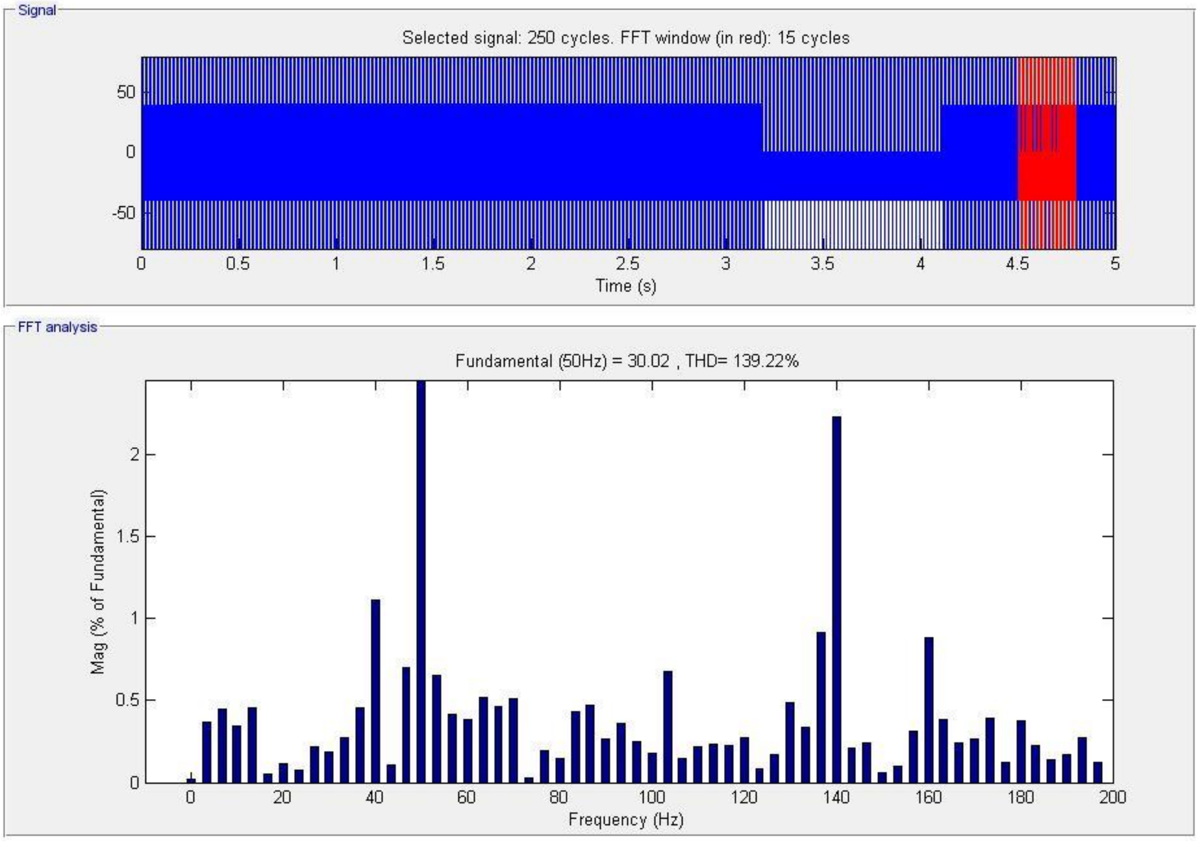

Fig 4.2(c)- FFT analysis of Voltage waveform

4.2.2. Current Output

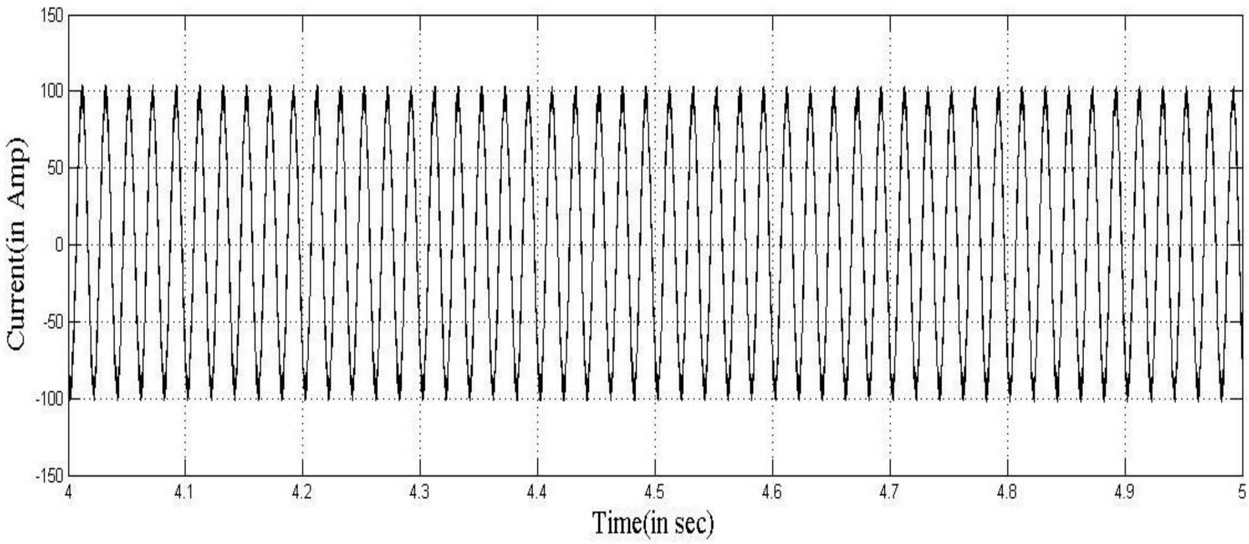

Fig 4.2(d) – Current vs Time graph of Inverter

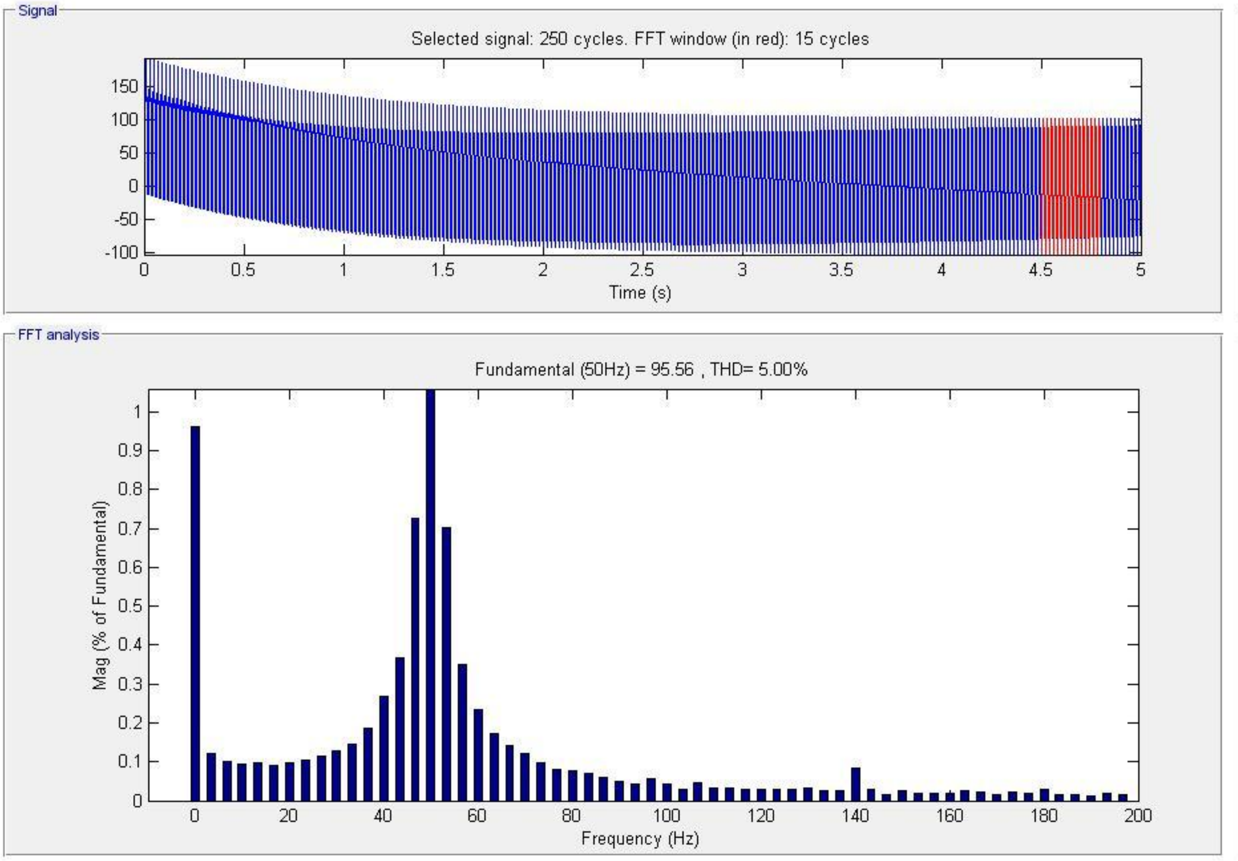

Fig 4.2(e) – FFT analysis of Current waveform

4.2.3. Output Active Power

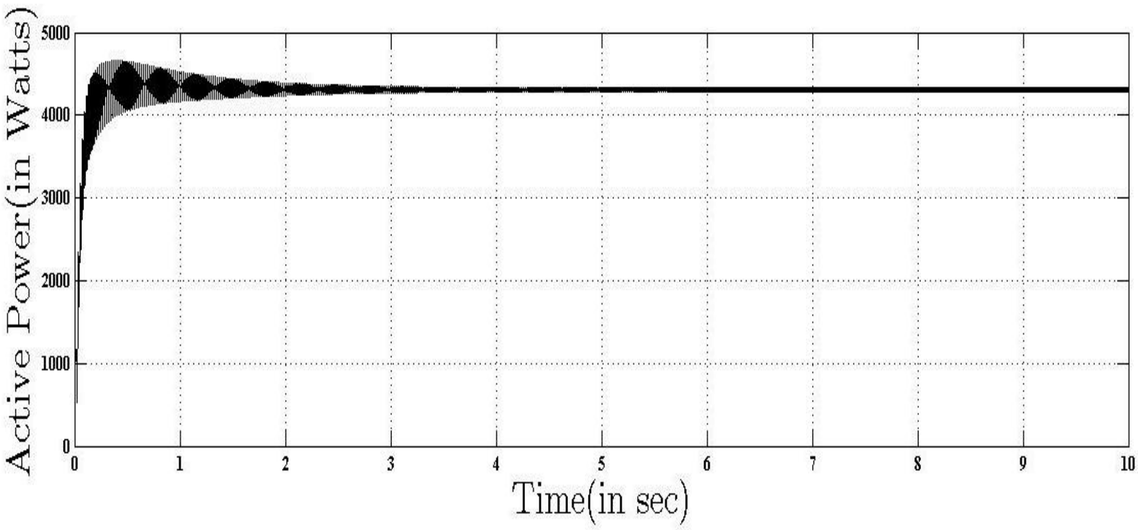

Fig4.2(f)- Output Active Power waveform

4.2.3. Output Reactive Power

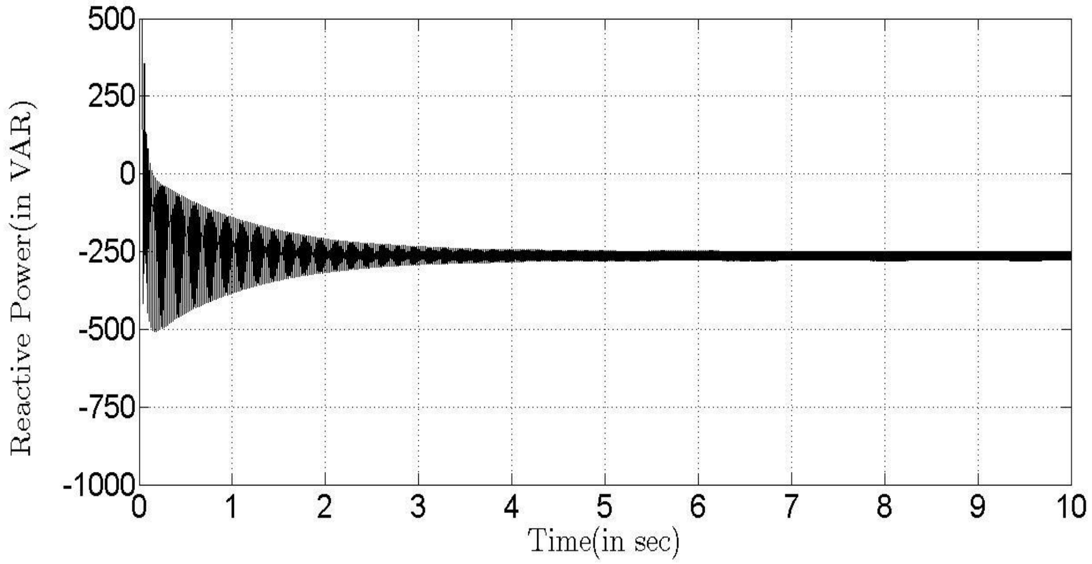

Fig4.2(g)- Output Reactive Power waveform

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Conclusion and

Future Recommendations

In this minor project, the inherent limitations of the conventional droop control scheme has been exposed. In order to achieve accurate proportional load sharing among parallel-operated inverters, the inverters should have the same per-unit resistive output impedances and the voltage set-points (E_i) should be the same. These are almost impossible to meet in reality. An improved droop control strategy is then proposed to obtain accurate proportional load sharing for micro-grids working in the standalone mode (and naturally also for micro-grids working in the grid-connected mode). This strategy does not require the above two conditions to be met in order to achieve accurate proportional sharing. The strategy is also able to compensate the voltage drop due to the load effect and the droop effect and the load voltage can be maintained within the desired range around the rated value. Quantitative analysis of the error in power sharing has been carried out thoroughly. Various experimental results have demonstrated that the strategy proposed here is very effective. The strategy proposed here is demonstrated for inverters with resistive output impedances but it can be applied to inverters with inductive output impedances by using the $Q - E$ and $P - \omega$ droop as well.

- Till now we have designed three phase inverter using SPWM technique, for the microgrid and studied Droop Controller and PLL .
- Further study will be done on Voltage and Current Control Units to generate desired value of modulation index and simulation will be done.
- Our very next objective is to connect inverters in parallel with proper droop control system to achieve a working mirogrid . This will be continued in the coming semester.

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