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A thesis on Robust Droop Controller for Accurate Proportional Load Sharing among Parallel Operated Inverters in Islanded Microgrid.

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DECLARATION

We do hereby declare that the thesis titled “**A thesis on Robust Droop Controller for Accurate Proportional Load Sharing among Parallel Operated Inverters in Islanded Microgrid.’’** Submitted to the department of Electrical and Electronic Engineering of International Islamic University Chittagong (IIUC) is our own effort, which is granted by our honorable supervisor. We will make sure that our thesis was not submitted before in the department of Electrical and Electronic Engineering of International Islamic University (IIUC).

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RECOMMENDATION

This is to certify that, Abdullah al Mohiuddin(ET103052) and Md. Asraful Mola(ET103066), students of International Islamic University Chittagong (IIUC) under the Department of Electrical and Electronic Engineering , has going to completed the thesis tilted on **“A thesis on Robust Droop Controller for Accurate Proportional Load Sharing among Parallel Operated Inverters in Islanded Microgrids.’’** precisely & successfully under my supervision.

Signature of the supervisor

………………........................

Engr. Mohammad Faisal

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May 2015

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Authos

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ABSTRACT

A microgrid is a part of a distribution network embedding multiple distributed generation systems like photovoltaic panels, small wind turbines etc. and storage systems. This paper focuses on the islanded operation of microgrids. In this mode of operation, the micro-sources are required to operate autonomously to regulate the local grid voltage and frequency. To make voltage and frequency stable, there have several control method in microgrid. The conventional droop control is typically used to achieve this autonomous voltage and frequency regulation. But conventional droop control has real and reactive power sharing limitations. To share the load accurately in proportion to their power ratings two condition should have met. The condition are the droop controllers must have same per unit output impedance and have same voltage set-point for the inverters. But it is difficult to meet in practice. In this paper, the inherent limitations of the conventional droop control scheme are revealed. That’s why robust droop controller is proposed which can share the load accurately without meeting the above conditions. It also help to reduce voltage drop due to load effect and droop effect. The robust works against numerical errors, disturbances, parameter drifts and component mismatches. In simulation part, the output shows the proportional load sharing among inverters.

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Chapter 1

Introduction

1.1 Background:

Energy is a key to the advancement and prosperity of humans. To keep doing the human development more energy is required. Microgrid can play important role in development of power crisis. There are different types of energy source such as wind energy, solar energy, wave energy etc. Microgrids are becoming an important concept to integrate DG and distributed energy storage systems [1-4]. The DGs in a microgrid should be controlled to ensure a stable operation in both grid connected and island modes operation. The control strategy is different for two different modes. The droop control is the basic control method for load current sharing. For grid connected operation, the system frequency and voltage of microgrid are mainly controlled by grid. However in absence of grid, the DGs in the microgrid need to be controlled such that the frequency and voltage of the microgrid are maintained within standard limits. Droop control employs locally measured variables to achieve equal p.u. real and reactive power sharing when operating in islanded mode. Mismatches in the inverter physical parameters and in the power line impedances that connect the inverters to the PCC degrade the power sharing accuracy. The additional reactive currents supplied by the inverters due to the unequal sharing do not allow the inverters to supply the maximum allowable real power and the real power sharing capabilities are not affected by these mismatches, as the frequency at steady state is constant throughout the whole microgrid. The additional reactive current supplied by each inverter reduces the maximum real power that can be supplied by inverters. This is the main problem of conventional droop control system. Due to this limitation, we proposed an improved droop control system to achieve accurate proportional load sharing which reduce the load voltage droop due to load effect.

1.2 Objectives:

Microgrid is going to be an important concept to integrate DG and distributed energy system. It can play an important role as a solution of power crisis. Generally in grid connected mode, it is easy to maintain the parameters of power system with Microgrid. But in Island mode, one or more primary or intermediate energy sources help to establish its voltage and frequency, otherwise, the microgrid will collapse. That’s mean there appear a problem for running the Microgrid. We have to control voltage and frequency within an acceptable limits. To meet this acceptable limit we have to execute some steps on the based on microgrid control system. The main objectives of our thesis is control of power sharing among two parallel connected inverters according to microgrid requirements such as:

i. Modeling of DG.
ii. Use appropriate control variable to control sharing of P and Q.
iii. Derive droop controller.
iv. Propose control strategy for islanded operation.
v. Accuracy of P and Q sharing in islanded mode.

1.3 A microgrid concept:

Due to the ever-increasing demand for high-quality and reliable electric power, the concept of distributed generation and energy storage has attracted widespread attention in recent years. Distributed generation and storage systems consist of relatively small-scale generation and energy storage devices that are interfaced with low- or medium-voltage distribution networks through power converters and can offset the local power consumption, or even export power to the upstream network if their generation surpasses the local consumption. An upcoming philosophy of operation which is expected to enhance the utilization of distributed generation and energy storage is known as the microgrid concept.

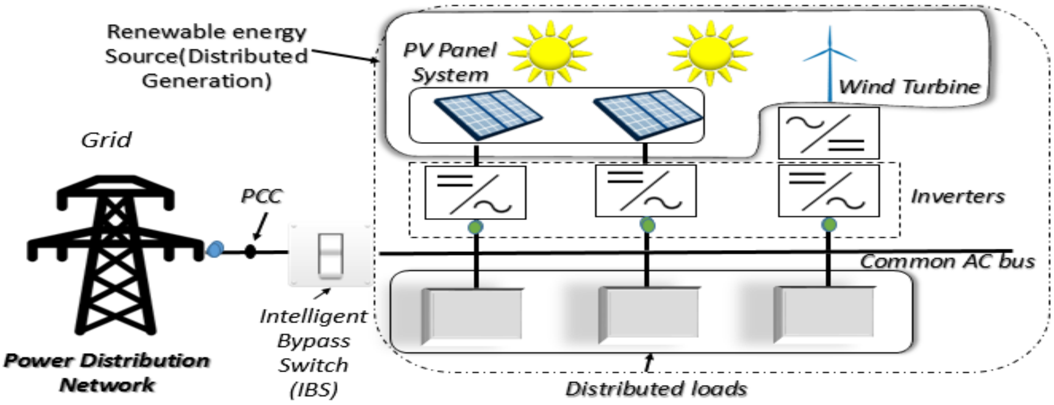


Fig. 1.1: Microgrid system.

The main benefits of microgrids are high energy efficiency, high quality and reliability of the delivered electric power, more flexible power network operation, and environmental benefits [5]. However, to achieve a stable and secure operation, a number of technical and economic issues have to be resolved before microgrids can become physically visible. In this paper, we deal with control methods for integrating distributed generation in grid-connected and islanded operation mode. The main components of a microgrid are:(i) distributed generation sources such as photovoltaic panels, small wind turbines, fuel cells, diesel and gas micro turbines etc.(ii) distributed energy storage devices such as batteries, super capacitors, flywheels and (iii)critical and non-critical loads. Energy storage devices are employed to compensate for the power shortage or surplus within the microgrid. They also prevent transient instability of the microgrid by providing power in transient. The transient power shortage in a microgrid can be compensated for by fast energy storage devices in the microgrid, or by the utility grid through a bidirectional power converter when operating in grid-connected mode.

1.4 Microgrid operation mode:

The microgrid can operate in grid connected mode or in island mode. In grid connected mode, the microgrid either draws or supplies power to the main grid depending on the generation and load mix and implemented market policies [6]. The microgrid can separate from the main grid whenever any error occur in the system.

1.4.1 Grid connected mode:

When a microgrid is grid connected, it behaves as a controllable load or source. It should not actively regulate the voltage at the PCC [7]. Furthermore, the harmonics and dc current it injects to the grid should be below the required levels. During this mode of operation, the primary function of the microgrid is to satisfy all of its load requirements and contractual obligations with the grid. That means the output sum of the power of the distributed generation systems is sufficient to charge the storage devices, any excessive power is supplied to the utility grid. If the sum of the power of the distributed generation and storage systems is deficient with respect to the load demand, the required power is supplied from the utility grid. In the grid-connected mode, power management is performed in a complementary manner between storage devices and as a result a DC microgrid can operate safely and efficiently.

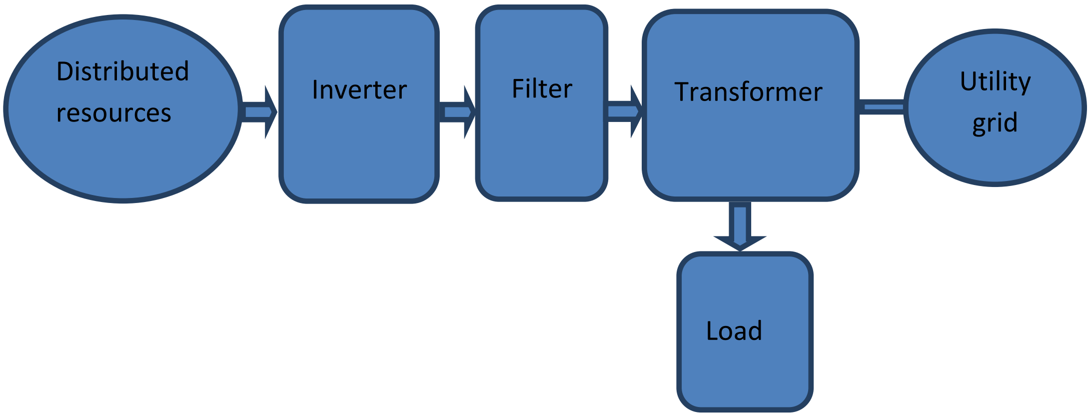


Fig. 1.2: Block diagram of grid connected mode in microgrid.

1.4.2 Island mode:

The microgrid should disconnected when an abnormal condition occurs in the grid. It shifts to island mode of operation, and the microgrid is faced with the following issues:

The voltage and frequency are established by the grid when the microgrid is connected. When the microgrid islands, one or more primary or intermediate energy sources help to establish its voltage and frequency, otherwise, the microgrid will collapse. Both voltage and frequency should be regulated within acceptable limits [8]. During the islanded mode, the battery plays the main role in regulating the DC link voltage level, and the supercapacitor plays a secondary role in responding of the sudden power requirement as an auxiliary source, for peak shaving during transients.

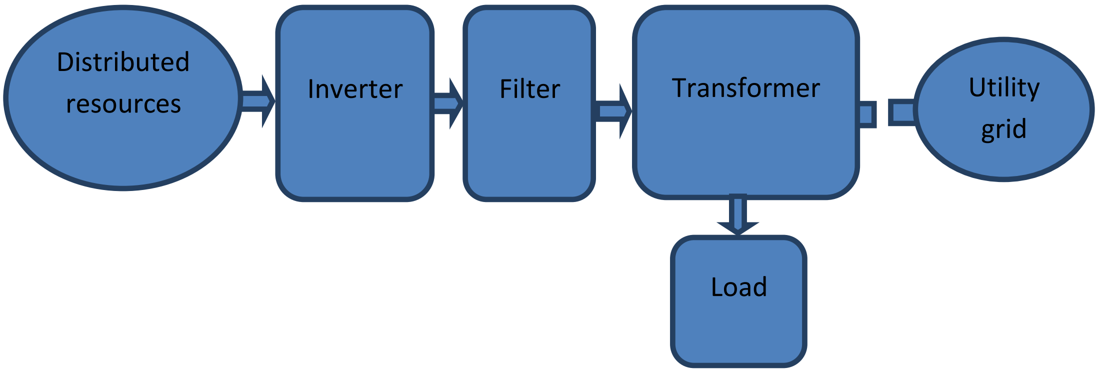


Fig. 1.3: Block diagram of island mode in microgrid.

CHAPTER 02

Literature Review

2.1 Introduction:

Microgrid is an important concept in development of power crisis. There are different types of energy source such as wind energy, solar energy, wave energy etc. Microgrid concept is to integrate DG and distributed energy storage systems. When microgrid disconnect from the utility grid in island mode, the voltage and frequency deviation occur which make problem in the system. That’s why the voltage and frequency should be controlled is an acceptable limit. For this we have to apply a control strategy named droop control strategy. The DGs in a microgrid should be controlled to ensure a stable operation in both grid connected and island modes operation. The control strategy is different for two different modes. The droop control is the basic control method for load current sharing.

2.2 Droop control system:

In microgrid, the system reliability and stability is achieved only by the voltage regulation when more micro sources are interconnected. This voltage regulation damps the reactive power oscillations and voltage. In a complex power system, when multiple DGs are attached to the microgrid, the power sharing among them is made properly with the help of a control strategy called droop control. Droop control also enables the system to disconnect smoothly and reconnect routinely to the complex power system [9].

The role of droop control in power sharing is that it control the real power on the basis of frequency droop control and it controls the reactive power on the basis of voltage control. The voltage and frequency can be manipulated by regulating the real and reactive power of the system. This forms a conventional droop control system.

2.3 Importance of microgrid:

Currently, most electricity is generated in centralized generating plants and transmitted to load centers through long overhead transmission lines. These centralized facilities are built away from load for economic, environmental and health and safety reasons. Due to rapid increases in the demand for electricity, generation will need to increase and the relevant infrastructures required for electricity transmission should be upgraded.

The increased load growth can be also catered for without expanding the existing network infrastructures by building decentralized generators located closer to customer loads. This is a more economical and environmentally friendly way of generating power. These small-to-medium sized generators distributed throughout a network are known as distributed generators (DGs). Most countries including Australia, are expecting to achieve the target of 20% renewable power by 2020. The deployment of DGs will help to reduce greenhouse gas emissions. Moreover, DGs can provide benefits for both electric utilities and consumers since they can reduce power loss, improve voltage profiles and reduce transmission and distribution costs.

2.4 Background of microgrid:

The world microgrid market reached $4 billion last year with North America claiming 74% of 2010’s total industry share, finds market research publisher SBI Energy. Fueled by rapidly growing solar, renewable energy and smart grid markets, the microgrid has become a viable solution to supply energy to local communities. There are different country have research centers on microgrid such as Consortium for Electric Reliability Technology Solutions (CERTS) and Power Systems Engineering Research Center (PSERC) in USA, The New Energy and Industrial Technology Development Organization (NEDO) in Japan, and CANMET Energy Technology Center in Canada.

2.5 Theory of droop control:

The role of droop control in power sharing is that it control the real power on the basis of frequency droop control and it controls the reactive power on the basis of voltage control [10]. The voltage and frequency can be manipulated by regulating the real and reactive power of the system. This forms a conventional droop control equation. In a transmission line, the real (P) and reactive power (Q) are designed as:

$$P = \frac{V_1 V_2}{X} \sin\delta \tag{2.1}$$

$$Q = \frac{V^2}{\mathrm{X}} - \frac{V_1 V_2}{\mathrm{X}} \cos\delta \tag{2.2}$$

In the above mentioned equation (1) and (2), Resistance (R) is neglected for an overhead transmission lines as it is much lower than inductance (L). Also the power angle δ is lesser, Therefore, sin δ = δ and $\cos\delta = 1$. Then we get from above equation:

$$\delta = \frac{XP}{V_1 V_2} \tag{2.3}$$

$$V_1 - V_2 = \frac{XQ}{V1} \tag{2.4}$$

Hence from the above equation (1.3) and (1.4), it is clear that the power angle δ can be controlled by regulating real power P. Also the voltage V_1 can be controlled through reactive power Q. dynamically, the frequency control leads to regulate the power angle and this in turn controls the real power flow [11]. Finally, the frequency and voltage amplitude of the microgrid are manipulated by adjusting the real and reactive power autonomously. As a result, the frequency and voltage droop regulation can be determined as:

$$f - f_o = K_p(P - P_o) \tag{2.5}$$

$$V - V_o = K_q(\text{Q-}Q_o) \qquad (2.6)$$

2.6 Types of droop control:

Droop control is categorised on the basis of regulating the system parameters. They are:

i. Conventional droop control
ii. Modified droop control

2.6.1 Conventional droop control:

This is a common type of droop control. Generally, the system frequency and the voltage amplitude are regulated with respect to the real and reactive power generation of the system. Hence the power sharing in microgrid is obtained by the output power generation according to its DG's power rating. The conventional droop control is further classified as:

i. Real power–frequency (P-F) droop control
ii. Reactive power–voltage magnitude (*Q-V)* droop control

2.6.2 Modified droop control:

In the case of conventional droop control, the resistance is taken as negligible quantity because L >>R in high voltage lines. Whereas this assumption is not suitable for microgrid as it operates at low and medium voltage. Hence modified droop control arise by changing the parameters of the conventional droop control as per their system requirement. The modified droop control referred in this work are:

i. P-V and Q-F droop control
ii. V-F droop control
iii. Adaptive transient droop
iv. SoC (State Of Charge) based droop control
v. Angle droop control
vi. Q-V dot droop control

CHAPTER 03

METHODOLOGY

3.1 Introduction:

The chapter belong to describe about conventional droop control system in broad which was discussed in chapter 1 shortly. There are some problem arise for equal load sharing between two inverters. Here also discussed the limitation of conventional droop control system. Due to limitation, a new droop control system is proposed name Robust droop control. The robust droop control is also described broadly.

3.2 Conventional droop conrtol:

The conventional drop control system is generally used to control the microgrid system for equal load sharing between two inverters operated in parallel. Generally, frequency and voltage regulate the real and reactive power of system. When inverter operated in parallel, some mismatch occur between two inverters which make obligation in case of load sharing. The inverter should have same per unit impedance and same RMS voltage set point to share the load accurately with proportional to their power ratings. . The advantage is that no external communication mechanism is required among the inverters to achieve good sharing for linear and non-linear loads. Adding an integral action to the droop controller is able to improve the accuracy of load sharing for grid-connected inverters. But it does not work for inverters operated in the stand-alone mode. Adding a virtual inductor and estimating the effect of the line impedance is able to improve the situation by changing the droop coefficients. To solve the power sharing problems for parallel-operated inverters are to make the output impedance as accurate as possible over a wide range of frequencies. Here the droop controller is discussed for R-inverters.

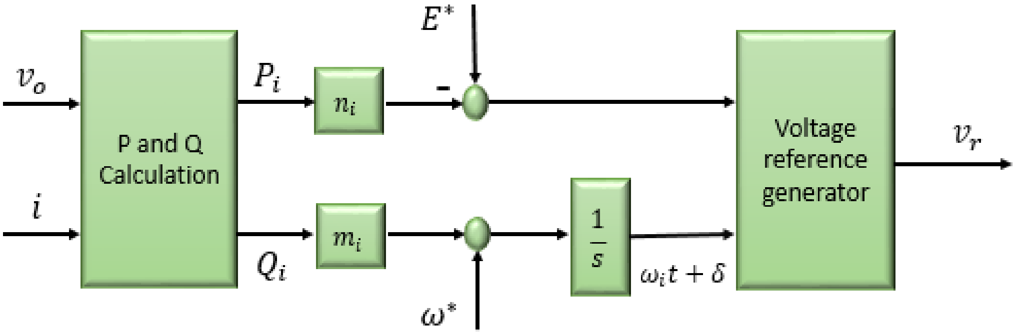


Fig. 3.1: Block diagram of conventional droop controller scheme [14].

The active and reactive power of each inverter injected into the bus [12], [13] are:

$$P = \frac{EV_o}{Z_o}\cos\delta - \frac{V_o^2}{Z_o} \tag{3.1}$$

$$Q = -\frac{EV_o}{Z_o}\sin\delta \tag{3.2}$$

In order for the inverters to share the load, the conventional droop controller should be:

$$\omega_i = \omega^* + m_i Q_i \tag{3.3}$$

$$E_i = E^* - n_i P_i \tag{3.4}$$

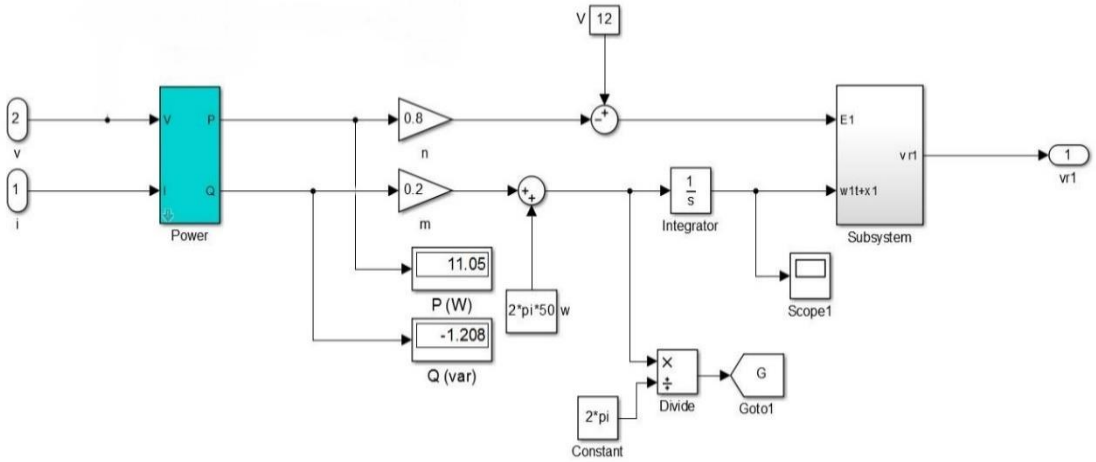


Fig. 3.2: Simulink model of conventional droop controller.

As shown in Fig. 3.1, is widely used to generate the amplitude and frequency of the voltage reference V_r for Inverter current i [14] [15],where ω^* is the rated frequency. Note that, from (2.2), the reactive power Q is proportional to -δ for a small power angle δ In order to make sure that the $Q - \omega$ loop is a negative feedback loop so that it is able to regulate the frequency, the sign before $m_i Q_i$ in (3.3) is positive, which makes it a boost term. The droop coefficientsn_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^*.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[10,29]. So that m_i and n_i should be like that,

$$n_1 S_1^* = n_2 S_2^* \qquad (3.5)$$

$$m_1 S_1^* = m_2 S_2^* \qquad (3.6)$$

It can also satisfied $\frac{n_1}{m_1} = \frac{n_2}{m_2}$.

3.3 Parallel operated inverters:

There are several reasons why inverters are needed to operate in parallel. One obvious reason is because of the limited availability of high current power electronic devices. Another reason is that parallel-operated inverters are able to provide system redundancy and high reliability needed by critical customers. Moreover, the parallel operation of inverters also eases the difficulties in thermal management and design for high-power inverters. When two inverters connected in parallel, the line impedance is omitted for assuming that the output impedances of the inverters are designed to dominate the impedance from the inverter to the AC-bus. The reference voltages of the two inverters are respectively,

$$V_{r1} = \sqrt{2}E_1 \sin(\omega_1 t + \delta_1) \qquad (3.7)$$

$$V_{r2} = \sqrt{2}E_2 \sin(\omega_2 \mathrm{t} + \delta_2) \qquad (3.8)$$

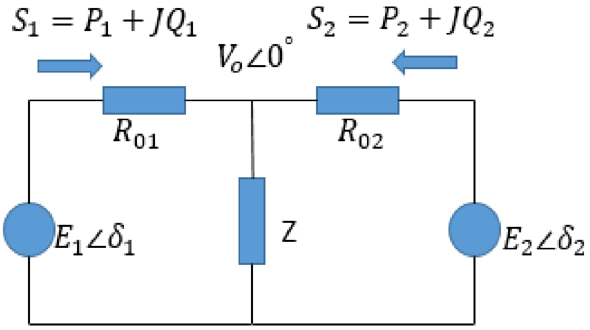


Fig. 3.3: Block diagram of two inverter connected in parallel [14].

The power ratings of the inverters are:

$$S_1^* = E^* I_1^* \qquad (3.9)$$

$$S_2^* = E^* I_2^* \qquad (3.10)$$

They share the same load voltage,

$$V_o = V_{r1} - R_{o1}i_1 = V_{r2} - R_{o2}i_2 \qquad (3.11)$$

When the load increases, the voltage droop occur. This is call load effect. Moreover, the robust droop controller is able to regulate the load voltage so that the voltage drop due to the load effect and the droop effect is reduced.

3.3.1 Power delivered to the voltage source:

When a voltage source V_r delivering power to another voltage source V_o through an impedance $Z_o\angle\theta$ since the current flowing through the terminal is I.

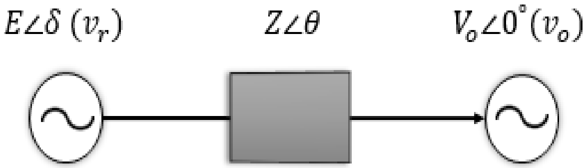


Fig. 3.4: Power delivered to a voltage source through an impedance [14].

Then we get

$$I = \frac{E\angle\delta - V_o\angle 0^\circ}{Z_o\angle\theta}$$

$$= \frac{E\cos\delta - V_o + J\sin\delta}{Z_o\angle\theta}$$

The real power and reactive power delivered by the source to the terminal via the impedance can then be obtained as

$$P = (\frac{EV_o}{Z_o}\cos\delta - \frac{V_o^2}{Z_o})\cos\theta + \frac{EV_o}{Z_o}\sin\delta\sin\theta \tag{3.12}$$

$$Q = (\frac{EV_o}{Z_o}\cos\delta - \frac{V_o^2}{Z_o})\sin\theta - \frac{EV_o}{Z_o}\sin\delta\cos\theta \tag{3.13}$$

Where δ the phase difference between the supply and the terminal is, often called the power angle. This actually express the situation when a voltage-controlled inverter is connected to an infinite bus where the terminal voltage is V_o. The real power and reactive power can be written as

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \sin\theta & \cos\theta \\ -\cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} \frac{EV_o}{Z_o}\sin\delta \\ \frac{EV_o}{Z_o}\cos\delta - \frac{V_o^2}{Z_o} \end{bmatrix}$$

Or, $\begin{bmatrix} \hat{P} \\ \hat{Q} \end{bmatrix} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix}$

Or, $\begin{bmatrix} \hat{P} \\ \hat{Q} \end{bmatrix} = \begin{bmatrix} \frac{EV_O}{Z_O}\sin\delta \\ \frac{EV_O}{Z_O}\cos\delta - \frac{V_O^2}{Z_O} \end{bmatrix}$

Hence, for a small δ,

$$\hat{P} = \frac{EV_o}{Z_o}\sin\delta \approx \frac{EV_o}{Z_o}\delta$$

$$\hat{Q} = \frac{EV_o}{Z_o}\cos\delta \approx \frac{E-V_o}{Z_o}V_o$$

Which means $\hat{P}$ and $\hat{Q}$ can be controlled by controlling δ and E separately. This is the basis of the widely-used droop control strategies.

3.3.2 For R-inverters:

A voltage-controlled inverter can be modelled as an ideal voltage source V_r in series with its output impedance $Z_o\angle\theta$ as shown in Figure 3.4. For different types of output impedances, different droop control strategies can be obtained. When the output impedance is resistive, $\theta = 0$.Then the equation of real and reactive power becomes,

$$P = \frac{EV_o}{Z_o}\cos\delta - \frac{V_o^2}{Z_o} \tag{3.14}$$

$$Q = -\frac{EV_o}{Z_o}\sin\delta \tag{3.15}$$

When δ is small, Then the equation will be

$$P = \frac{V_o}{Z_o}\mathrm{E} - \frac{V_o^2}{Z_o}$$

$$Q = -\frac{EV_o}{Z_o}\delta$$

That's mean we can say the real power is proportional to the voltage ($P \sim E$) and the reactive power is proportional to the negative power angle ($Q \sim - \delta$).

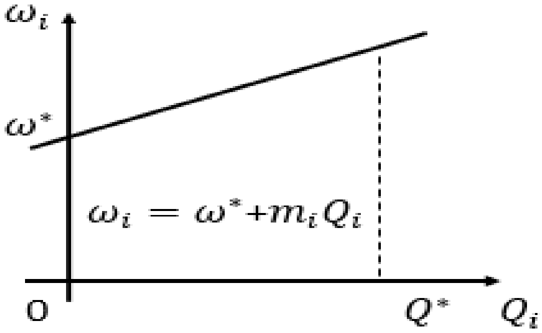


Fig. 3.5: Frequency droop for R-inverter [14].

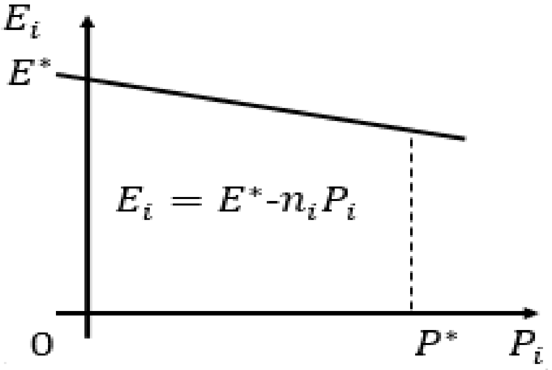


Fig. 3.6: Amplitude droop for R-inverter [14].

Where $\sim$ means in proportion to. Hence, the conventional droop control strategy takes the form,

$$\omega_i = \omega^* + m_i Q_i$$

$$E_i = E^* - n_i P_i$$

This strategy, consisting of the $Q - \omega$ and $P - E$ droop, is illustrated in Figure 3.3 and Figure 3.4. In this case, $\hat{P} = -Q$ and $\hat{Q} = P$.

3.4 Inherent limitation of conventional droop controller:

From the study of conventional droop control system, some limitation have been observed which create problem for proportional load sharing between two inverters without respective conditions. The problem are:

- The inverter should have same per unit impedance to share equal load among inverters.
- The RMS voltage set point for the inverters should be same for equal load sharing.
- Adding an integral action to the droop controller is able to improve the accuracy of load sharing only for grid connected inverter. It does not work in stand-alone mode.

Usually, the inverter output impedance is inductive because of the output inductor and the highly inductive line impedance. In low-voltage applications, the line impedance is normally resistive. It is better to force the output impedance to be resistive [12] [13] [17] because its impedance does not change with the frequency. The droop control strategy has different forms according to the type of the output impedance [12] [17]. The $Q - E$ and $P - \omega$ droop is used when the output impedance is inductive; the $Q - \omega$ and $P - E$ droop is used when the output impedance is resistive. In this paper, the analysis will be done for the $Q - \omega$ and $P - E$ droop.

3.4.1 Real power sharing:

The real power of two inverter can be obtained by the following equation,

$$P_i = \frac{E^* \cos\delta_i - V_o}{n_i \cos\delta_i + \frac{R_{oi}}{V_o}}$$

The voltage deviation of the two inverters lead to considerable error in load sharing. The voltage deviation ΔE should be zero. This is a very strict condition because there always occur numerical computational errors, disturbances, parameter drifts and component mismatches which is the main problem for load sharing precisely. The condition is,

$$\frac{n_1}{R_{o1}} = \frac{n_2}{R_{o2}}$$

That's means n_i should be chosen to be proportional to its output impedance R_{o1}. For achieving accurate real power share, the output impedance can be design as,

$$R_{o1}S_1^* = R_{o2}S_2^*$$

The per unit output impedance of the parallel operated inverters should be same to achieve proportional real power sharing for the conventional droop control system. For accurate sharing virtual output impedance is considered. And voltage set point E_i should be same otherwise error appears in real power sharing [18]. From equation (3.4) we get the real power deviation ΔP_i due to the voltage set-point deviation ΔE_i is,

$$\Delta P_i = -\frac{1}{n_i}\Delta E_i \qquad (3.16)$$

The voltage droop ratio of the inverter is $\frac{n_i P_i^*}{E^*}$ at rated power. If the droop coefficient is small then the real power sharing error will be large. Similarly if the voltage set point deviation is large, then the sharing error will be bigger.

3.4.2 Reactive power sharing:

From equation (3.3), we have seen that reactive power sharing of the inverter depends on frequency since the output impedance of the inverter is considered as resistive. If the system is in the steady state, then two inverters operate under the same frequency. It is ensure the accuracy of sharing reactive power for inverters.

It can be express a $m_1 Q_1 = m_2 Q_2$. The droop coefficient m_i should be chosen that the reactive power sharing is proportional to their power ratings [19]. That's means

$$\frac{Q_1}{S_1^*} = \frac{Q_2}{S_2^*} \qquad (3.17)$$

3.5 Output impedance control of inverter:

It is very simple controller designed on the basis of the idea of the virtual impedance concept [18], to force the output impedance to be resistive. In Figure (3.7) each inverter's control signal u is converted to a PWM signal to drive the IGBT-bridge. So that the average of u_f over a switching period is the same. That's mean $u_f = u$. The inductor current I is measured to construct a controller so that the output impedance of the inverter is becoming resistive and to dominate the impedance between the inverter and the ac bus.

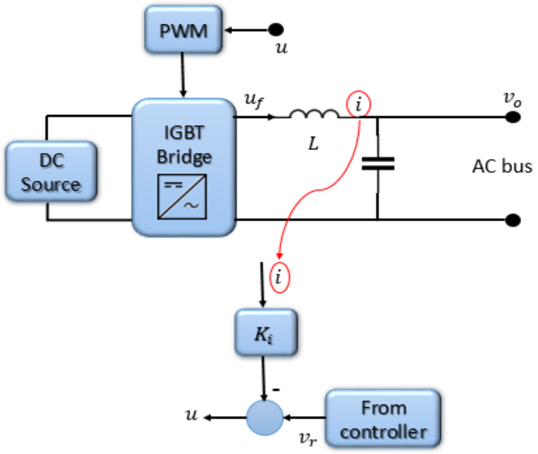


Fig. 3.7: A simple controller to achieve resistive output impedance [14].

If the gain K_i is chosen big enough, the output impedance will be purely resistive over a wide range of frequencies. And the effect of the inductance is negligible. That's mean that

$$Z_o(s) \approx R_o = K_i \tag{3.18}$$

If we consider the value of K_i is same for both inverters, then the per-unit output impedances of the two inverters significantly different. This is occur due to different Feeder impedances or component mismatches. In our thesis we consider the value of K_i is 2:1 for two inverters which make different per unit impedance for inverters.

3.6 Robust droop controller:

It is difficult to maintain $E_1 = E_2 \ or \ \delta_1 = \delta_2$ because there are always numerical computational errors, disturbances and noises. It is also difficult to maintain different feeder impedances. The reality is that none of these conditions would be met although the reactive power sharing is accurate. A system is needed to make accurate proportional load sharing and the system is known is robust droop controller.

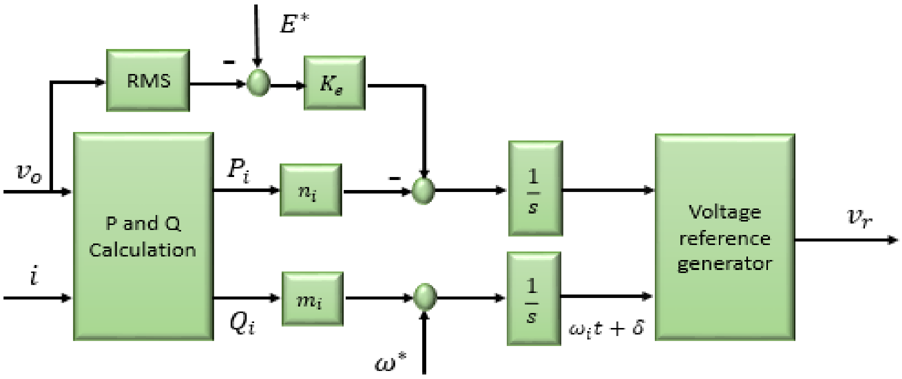


Fig. 3.8: Block diagram of proposed robust droop controller [14].

The voltage droop can be written as

$$\Delta E_i = -n_i P_i \tag{3.19}$$

This equation works for the grid-connected mode where ΔE_i is normally zero. So that the desired power is sent to the grid without error. It does not work for the standalone mode because the power P_i is determined by the load cannot be zero [21-23]. If we can design such a controller which can operate in both grid connected and island mode and not to need change when the operation mode changes, then it would be superb. And also the change of controller could be avoided when the operation mode changes.

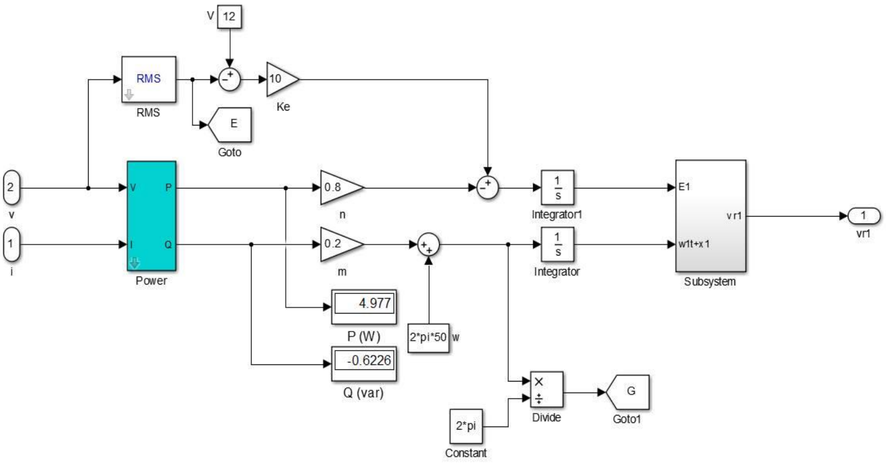


Fig. 3.9: Simulink model of robust droop controller.

The voltage droop occur due to load effect and droop effect. The droop coefficient n_i should be small to reduce the voltage drop. But small droop coefficient response slowly in the system. We have to maintain the voltage in a certain level so that it response fast in the system. The load voltage drop $E^* - V_o$ needs to be fed back in a way so that it can be added to ΔE_i via an amplifier K_e. That's why robust droop controller can eliminate computational errors, noises and disturbances. It is also able to maintain accurate proportional load sharing and hence with parameter drifts, component mismatches and disturbances.

In the steady state, the input to the integrator should be 0. For robust droop controller we get

$$n_i P_i = K_e(E^* - V_o) \qquad (3.20)$$

In above equation, the value of K_e is always same among parallel operated inverters. That’s why accurate real power sharing occur without having same voltage set-point. So the real power sharing don’t depends on inverter output impedance.

CHAPTER 04

SIMULATION RESULT AND DISCUSSION

4.1 Parallel operated inverters in island mode for robust controller:

Here two inverters operated in parallel and the output impedance of the inverters is considered as resistive. Two different types of controller such as conventional droop controller and robust droop controller have been used and output are analysed for both controllers used in the system. Fig. 4.1 is our proposed Matlab Simulink model for our thesis.

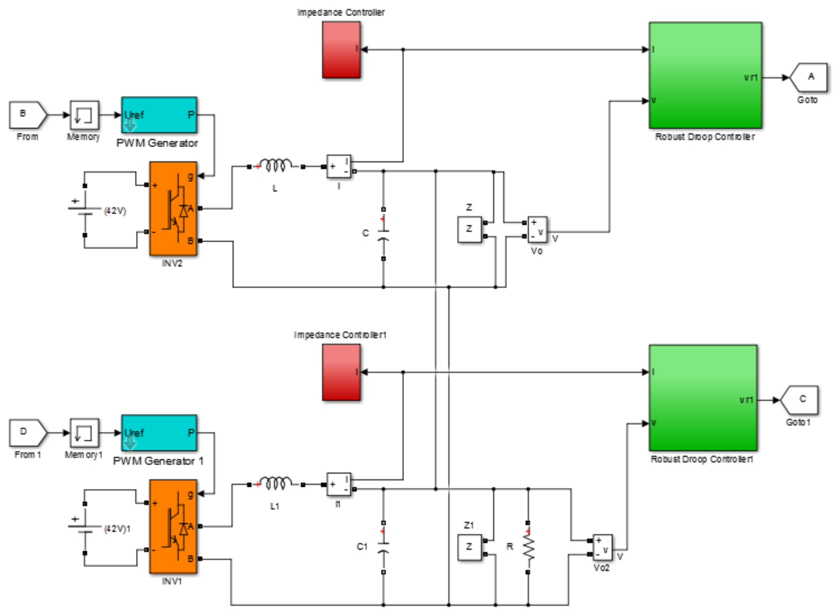


Fig. 4.1: Simulink model of parallel operated inverters.

In this simulation, two separate 42 V dc voltage supplies are used. The dc signal is inverted using single phase full bridge IGBT/Diodes inverter. The switching frequency of the PWM generator is 7.5 kHz. The frequency of the system is 50 Hz. The values of the inductors are 2.35 mH and capacitors are 22µF. The rated voltage of the system is 12 V RMS. The value of the load resistor is 9 Ω.

4.2 Different per unit output impedance to achieve 2:1 power sharing:

For different per unit output impedance, we considered the value of K_i is 4 for both inverters which makes the output impedance of inverters is different. This could be happened in reality due to different feeder impedances. Component mismatches are also responsible for different per unit output impedance.

4.2.1 Real power sharing:

To achieve the real power sharing 2:1 between two inverters the droop coefficient are assumed that $n_1 = 0.4$; $n_2 = 0.8$. The rated voltage is 12V RMS and $K_e = 10$. So that the ratio 2:1 real power can be achieved. That means $P_1 = 2P_2$.

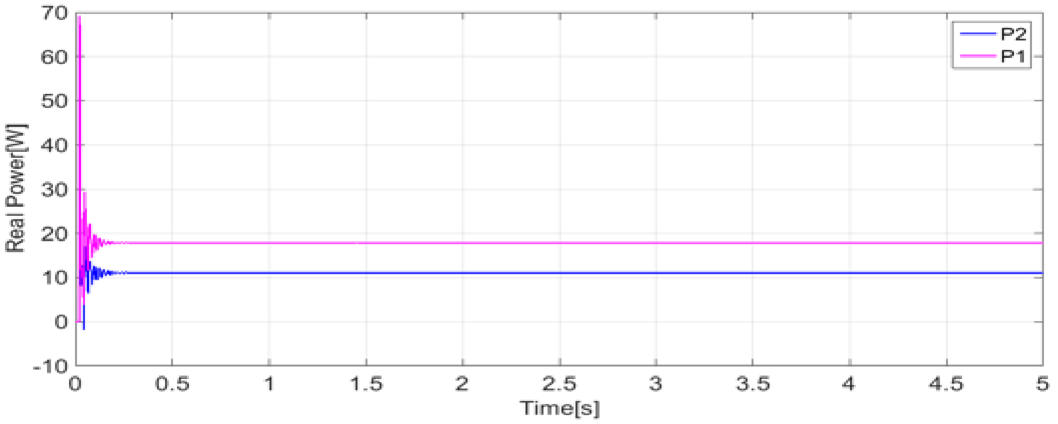


Fig. 4.2: Output of real power for conventional droop controller.

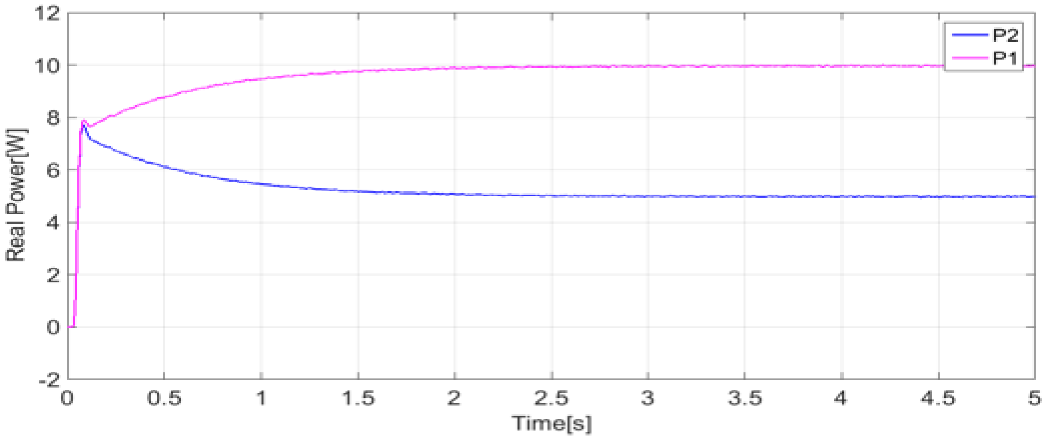


Fig. 4.3: Output of real power for robust droop controller.

For different per unit output impedance 2:1 real power is achieved in case of robust droop controller shown in Fig. 4.3 as it has no effect on inverter output impedance. The output shows that after 1.5 second inverter 1 and inverter 2 share the load 10 watt and 5 watt respectively which defined the sharing ratio 2:1. But for conventional droop controller shown in Fig. 4.2 the 2:1 real power sharing is not achieved due to its limitation. That means it must have same per unit impedance for proportional load sharing.

4.2.2 Reactive power sharing:

To achieve the reactive power sharing 2:1 between two inverters the droop coefficient are assumed that $m_1 = 0.1$; $m_2 = 0.2$. The system frequency is 50 Hz and $K_e = 10$. So that the sharing ratio 2:1 of reactive power can be achieved. That's mean $Q_1 = 2Q_2$.

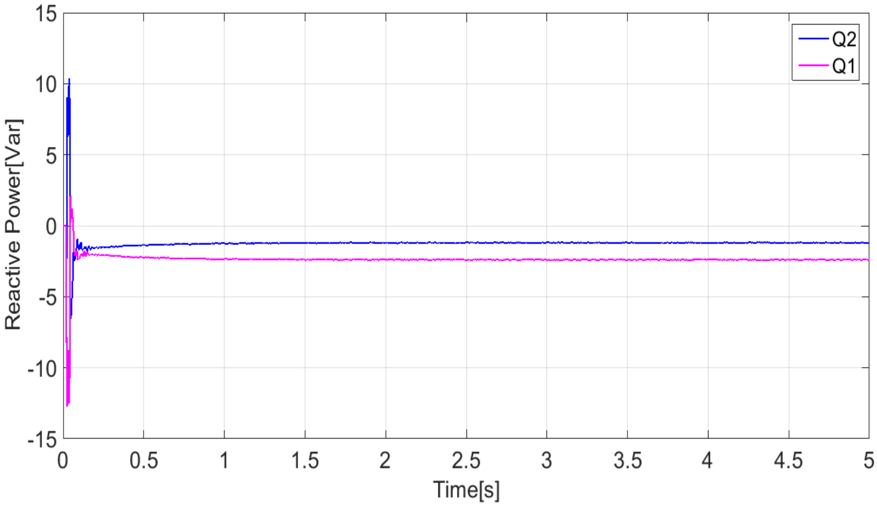


Fig. 4.4: Output of reactive power for conventional droop controller.

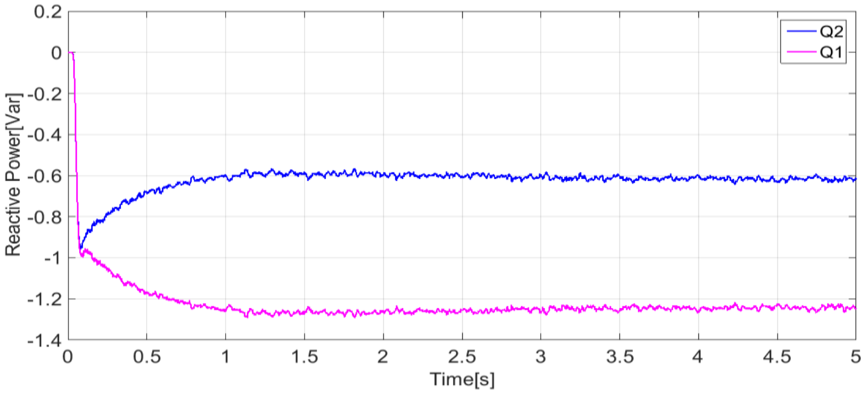


Fig. 4.5: Output of reactive power for robust droop controller.

Both of the inverters have resistive output impedance and the system is in steady state. So the frequencies of the two inverters are same i.e. $\omega_1 = \omega_2$. So reactive power sharing is easily achieved for inverters having resistive output impedances. Both the conventional and robust droop controller share reactive power in 2:1 ratio in Fig. 4.4 and Fig. 4.5 respectively.

4.2.3 RMS output voltage analysis:

The RMS output voltage of conventional droop controller is near 17 V shown in Fig. 4.6 where rated voltage is 12V RMS. But in case of robust droop controller the RMS output voltage is near 12V shown in Fig. 4.7.

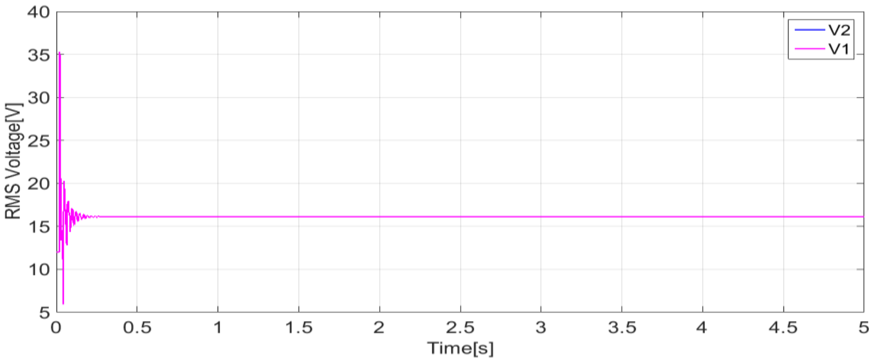


Fig. 4.6: Output RMS voltage for conventional droop controller.

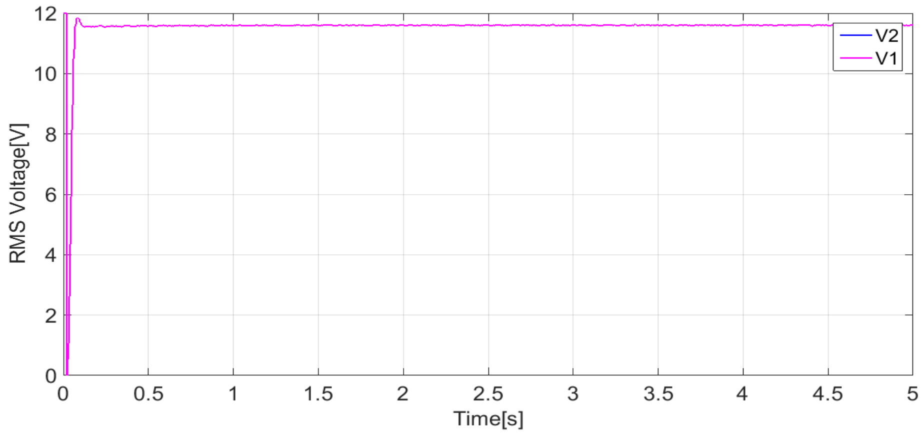


Fig. 4.7: Output RMS voltage for robust droop controller.

4.2.4 Voltage set point analysis:

For proportional load sharing voltage set point should be same in case of conventional droop controller otherwise it does not share the load proportionally between two inverters. Since here voltage set points for conventional droop controller are not same in Fig. 4.8, it causes error in real power sharing.

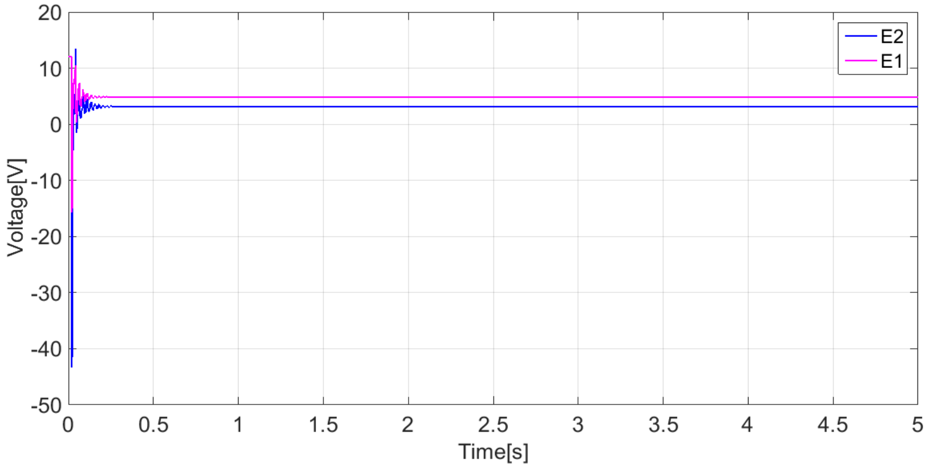


Fig. 4.8: Output of voltage set point for conventional droop controller.

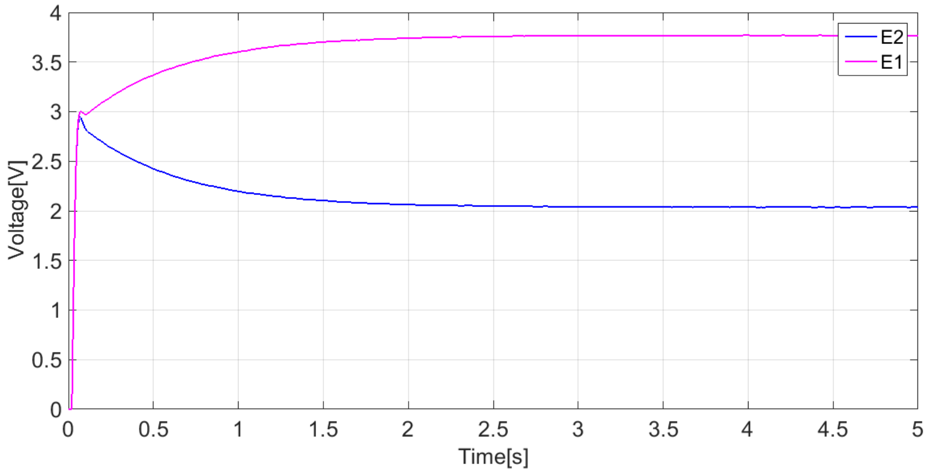


Fig. 4.9: Output of voltage set point for robust droop controller.

But in case of robust droop controller, for real power sharing it is no matter that the voltage set point should be same or not. In Fig. 4.9 voltage set point is different but the 2:1 real sharing is achieved for robust droop controller.

4.2.5 Frequency analysis:

The frequency is almost same in both robust droop controller and conventional droop controller. The value of frequency in conventional droop controller and robust droop controller is 49.500 HZ and 49.850 HZ respectively.

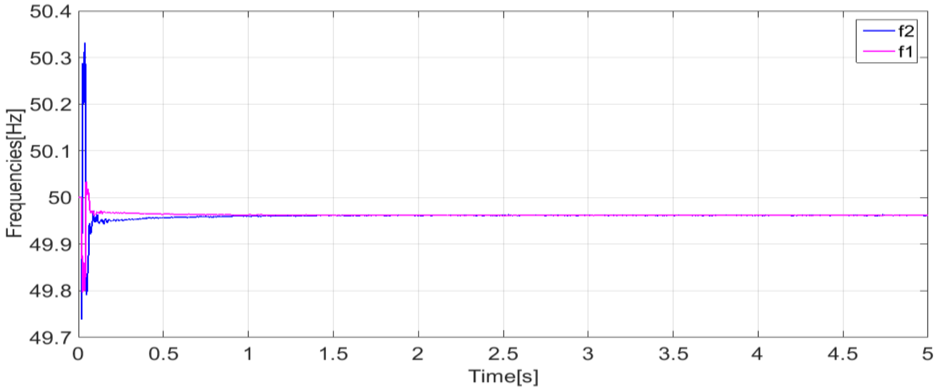


Fig. 4.10: Output of frequencies for conventional droop controller.

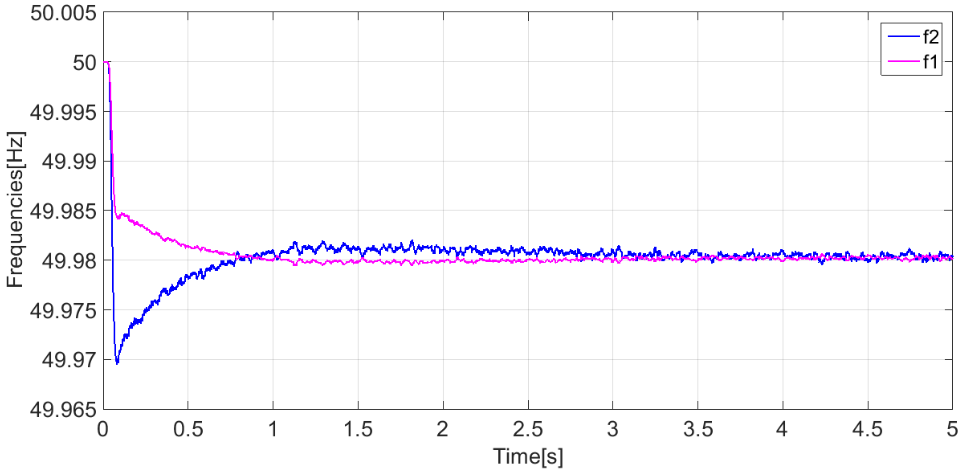


Fig. 4.11: Output of frequencies for robust droop controller.

4.2.6 Current analysis:

The current sharing for the two inverters reflect power sharing. The current curve for conventional droop controller shown in Fig. 4.12 is not sharing in 2:1 ratio. Robust droop controller shown in Fig. 4.13 is almost sharing current in 2:1 ratio.

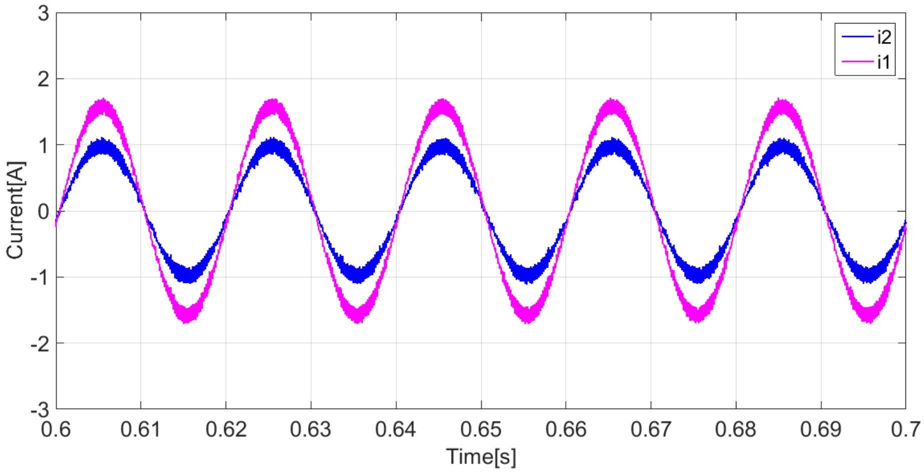


Fig. 4.12: Output of current for conventional droop controller.

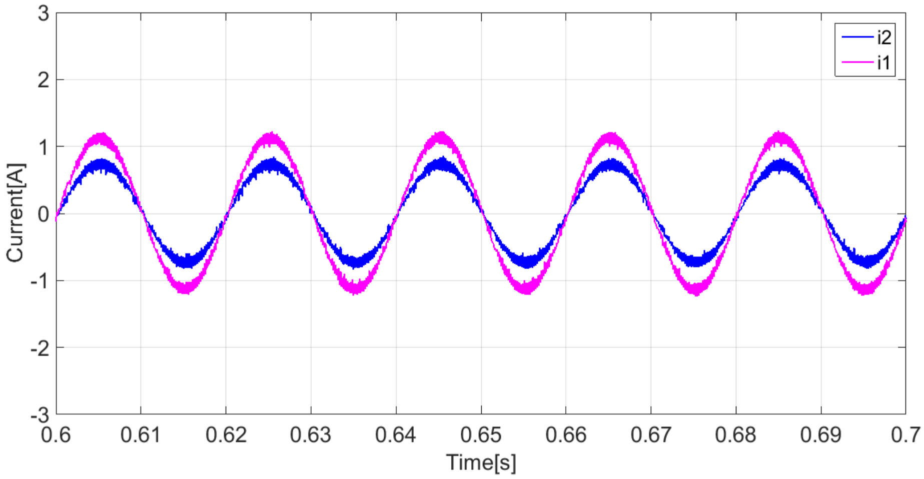


Fig. 4.13: Output of current for robust droop controller.

4.3 Same per unit output impedance to achieve 2:1 power sharing:

For same per unit output impedance, the value K_i for both inverters should be like that as it the per unit output impedance of two inverters remain same. Here we considered value of K_i is 2 and 4 for two inverters respectively. Which make the values of per unit output impedance of inverters same.

4.3.1 Real power sharing:

To achieve the real power sharing in 2:1 ratio between two inverters the droop coefficient are assumed that $n_1 = 0.4$; $n_2 = 0.8$. The rated voltage is 12 V RMS and $K_e = 10$ so that the ratio 2:1 real power is achieved. That's mean $P_1 = 2P_2$.

For same per unit output impedance 2:1 real power sharing is achieved in case of robust droop controller shown in Fig. 4.15 as it has no effect on inverter output impedance. The output shows that inverter 1 and inverter 2 share the load 10 watt and 5 watt respectively which defined the sharing ratio 2:1. Conventional droop controller also shown in Fig. 4.14, the 2:1 real power sharing is still not achieved. This is due to numerical computational error, noises or disturbances. There is still some errors but it is improved than previous as we tried to keep the per unit output impedances for both inverter to be same.

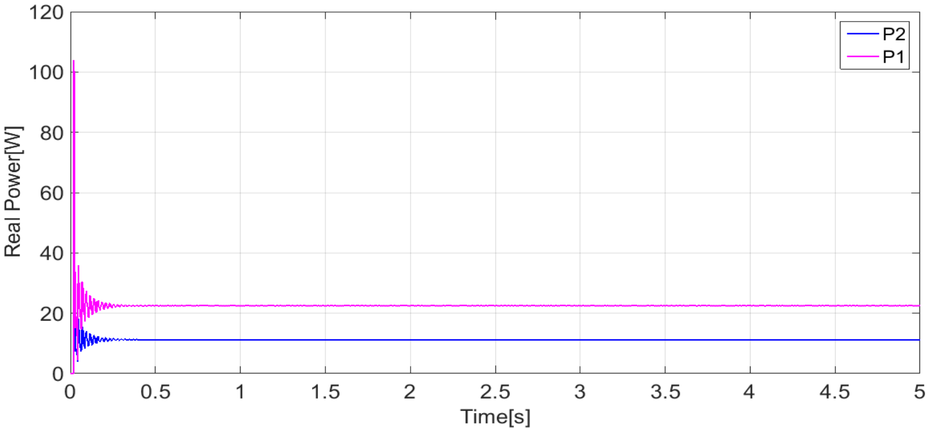


Fig. 4.14: Output of real power for conventional droop controller.

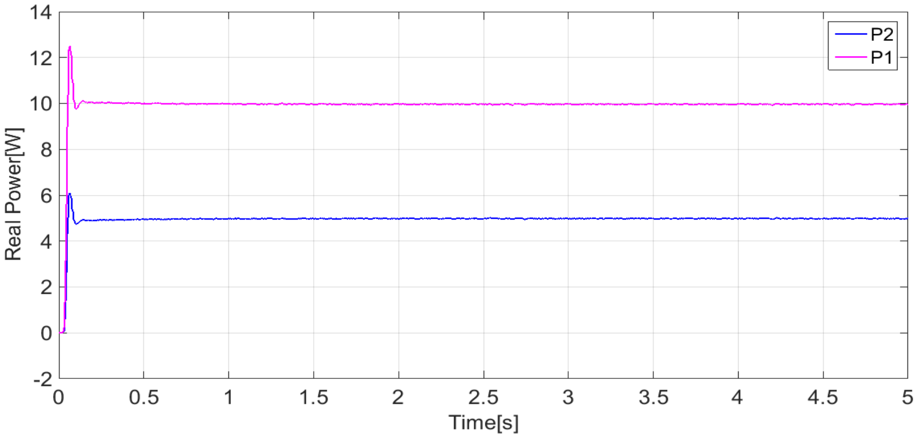


Fig. 4.15: Output of real power for robust droop controller.

4.3.2 Reactive power sharing:

To achieve the reactive power sharing 2:1 between two inverters the droop coefficient are assumed that $m_1 = 0.1$; $m_2 = 0.2$. The system frequency is 50 Hz and $K_e = 10$. So that the sharing ratio 2:1 of reactive power can be achieved. That means $Q_1 = 2Q_2$.

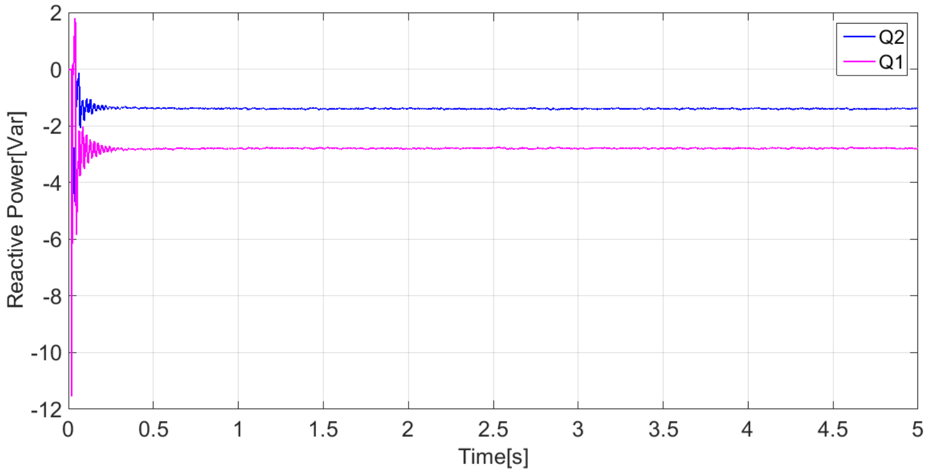


Fig. 4.16: Output of reactive power for conventional droop controller.

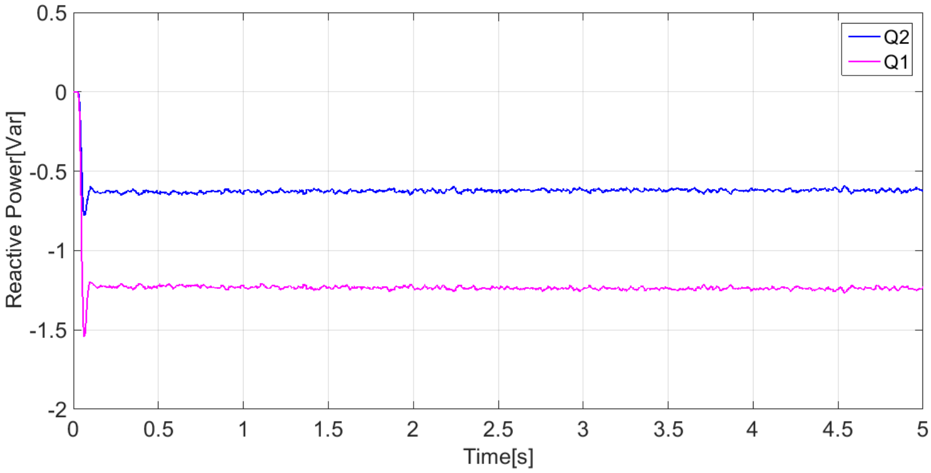


Fig. 4.17: Output of reactive power for robust droop controller.

For same per unit output impedance 2:1 reactive power sharing is achieved in case of robust droop controller shown in Fig. 4.17 and also for conventional droop controller shown in Fig. 4.16. As the output impedances of the inverters are resistive and the system is in steady state, frequencies remain the same for both inverters i.e. $\omega_1 = \omega_2$. This guarantees reactive power sharing in 2:1 ratio.

4.3.3 RMS output voltage analysis:

The RMS output voltage of conventional droop controller is near 17 V shown in Fig. 4.18 where rated voltage is 12V RMS. But in case of robust droop controller the RMS output voltage is near 12V shown in fig.4.19. It is as like as same to the value of different per unit output impedance. That means it does not depends on output impedances.

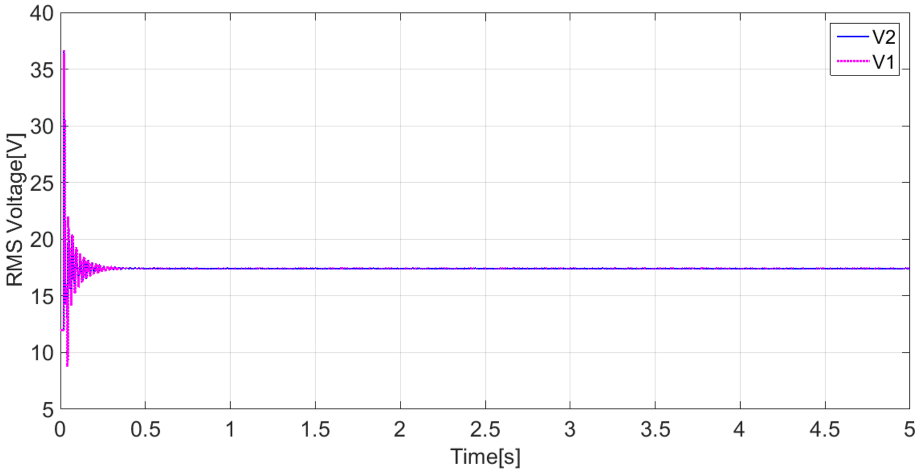


Fig. 4.18: Output of RMS voltage for conventional droop controller.

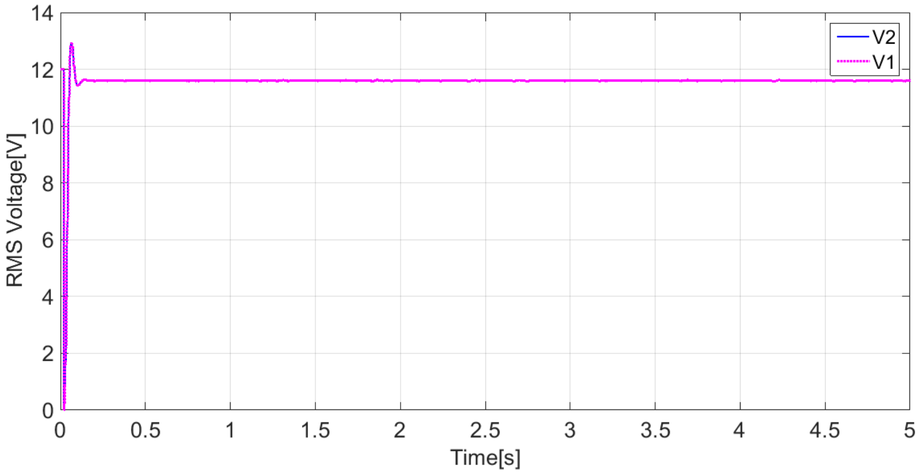


Fig. 4.19: Output of RMS voltage for robust droop controller.

4.3.4 Voltage set point analysis:

For conventional droop controller in Fig. 4.20 the voltage set points for two inverters are same. Although there is some error in real power sharing in conventional droop controller, the same voltage same points improved the real power sharing for conventional droop controller.

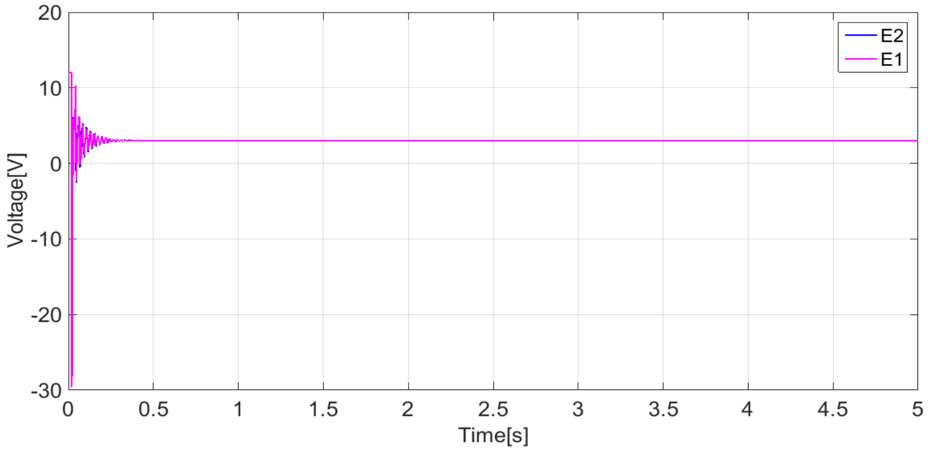


Fig. 4.20: Output of voltage set point for conventional droop controller.

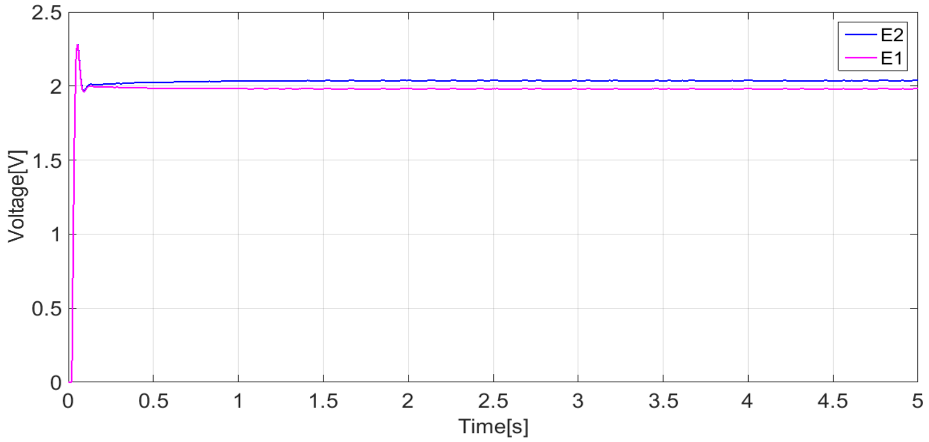


Fig. 4.21: Output of voltage set point for robust droop controller.

But in case of robust droop controller, it is no matter that the voltage set point should be same or not for share the load proportionally. In Fig. 4.21 voltage set point is a little bit different but the 2:1 sharing is achieved in load sharing.

4.3.5 Frequency analysis:

The frequencies are almost same for both robust droop controller and droop controller. The value of frequency in conventional droop controller and robust droop controller is 49.97 HZ and 49.98 HZ respectively. Since the output impedance is equal therefore the frequency is also same. Because the output impedance vary with frequency.

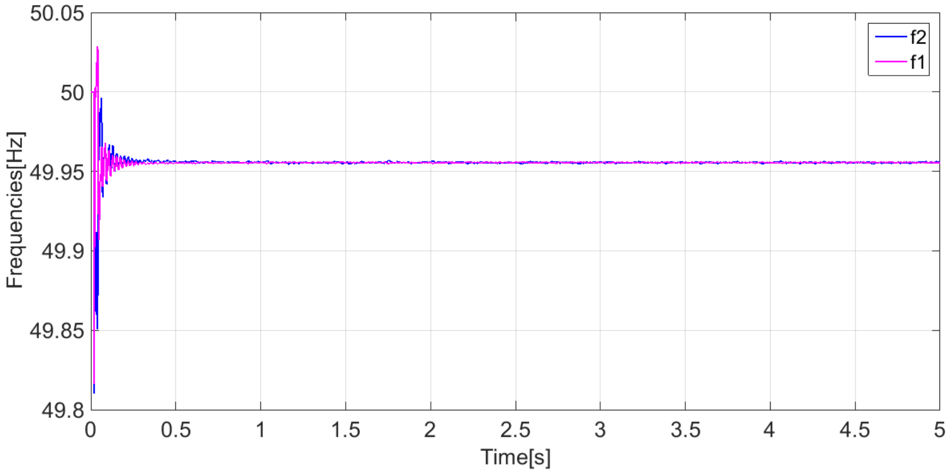


Fig.4.22: Output of frequencies for conventional droop controller.

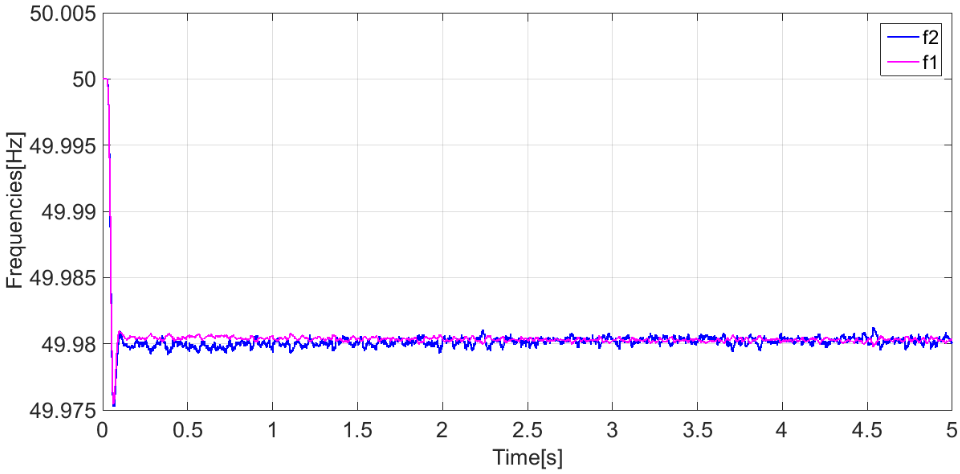


Fig.4.23: Output of frequencies for robust droop controller.

4.3.6 Current analysis:

The current sharing which is inductor current reflects power sharing. The current curve for conventional droop controller shown in Fig. 4.24 and robust droop controller is shown in Fig. 4.25. These current curves are improved than current curves we get using different per unit impedance.

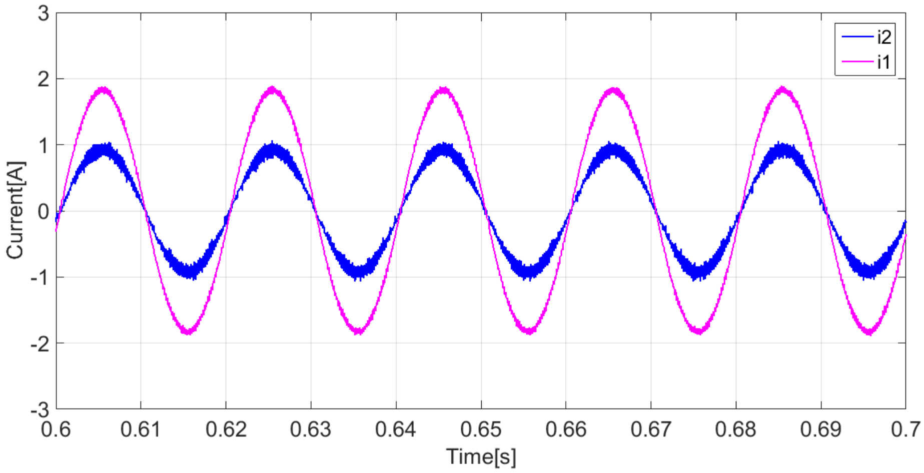


Fig.4.24: Output of current for conventional droop controller.

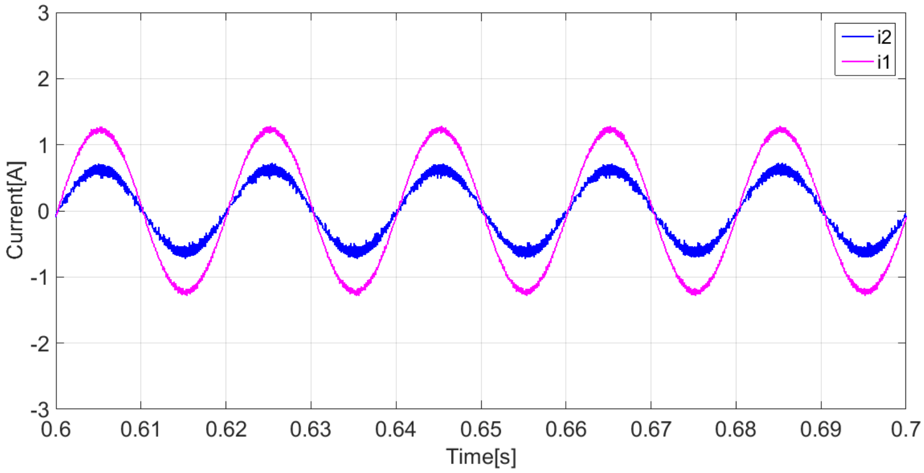


Fig.4.25: Output of current for robust droop controller.

4.4 Robust droop controller with $K_e = 1$:

Robust droop controller with K_e demonstrate the role K_e. It can be seen that a large K_e helps speed up the response of the system and reduce the voltage drop.

4.4.1 Real power sharing:

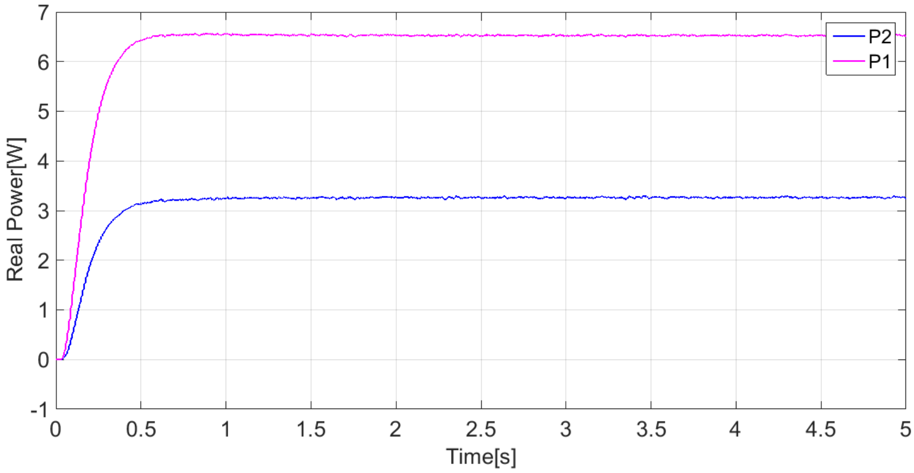


Fig.4.26: Output of real for robust droop controller.

4.4.2 Reactive power:

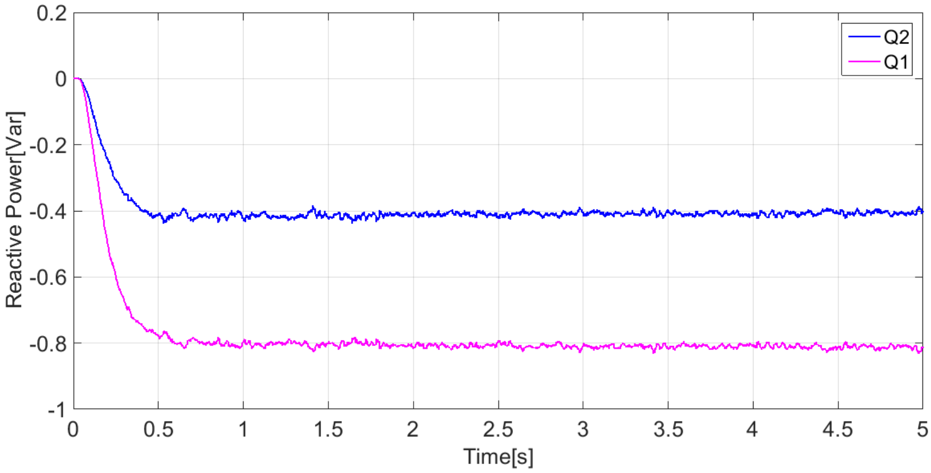


Fig.4.27: Output of reactive for robust droop controller.

4.4.3 RMS output voltage:

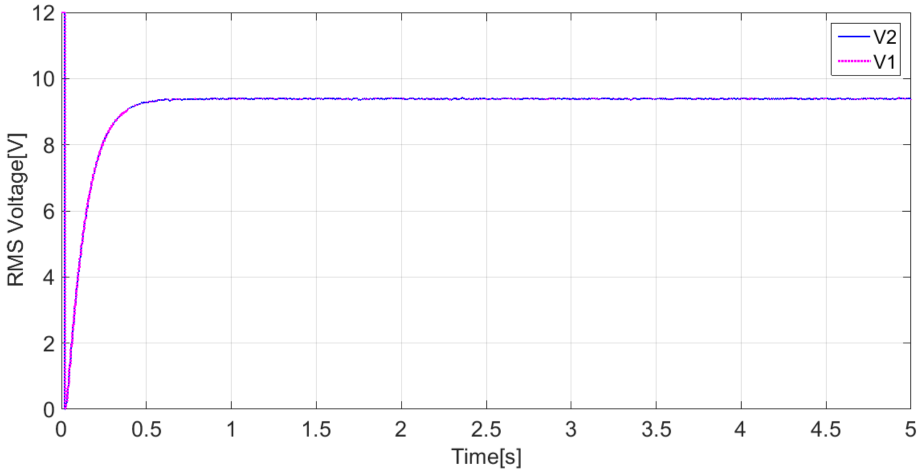


Fig.4.28: RMS output voltage for robust droop controller.

4.4.4 Voltage set point:

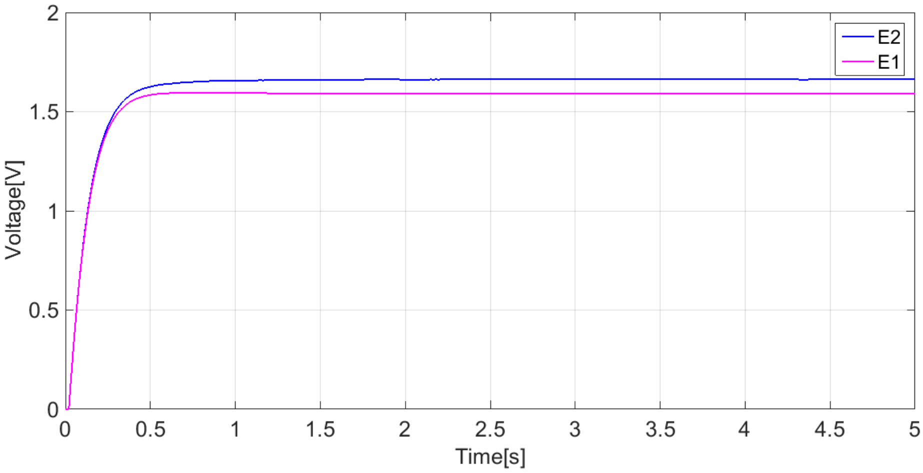


Fig.4.29: Voltage set point for robust droop controller.

4.4.5 Frequency:

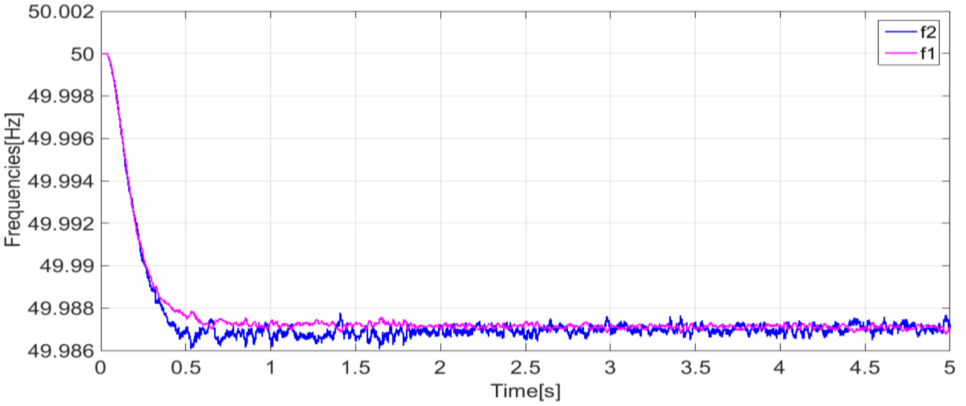


Fig.4.30: Frequency for robust droop controller.

4.5.6 Current:

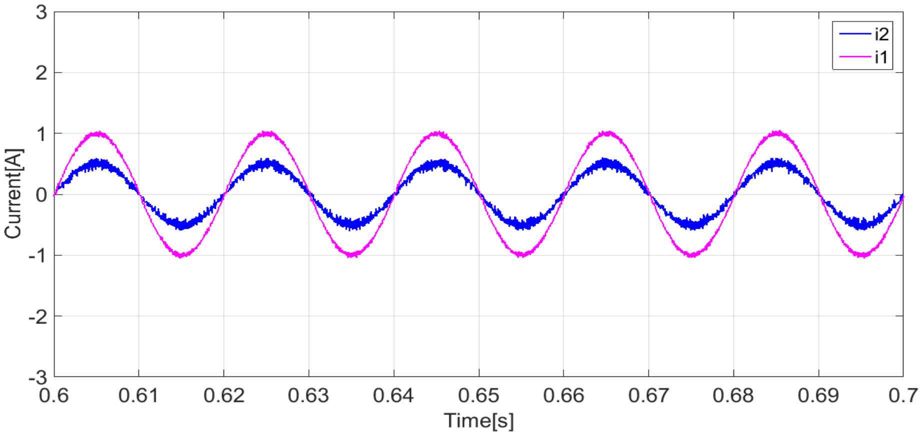
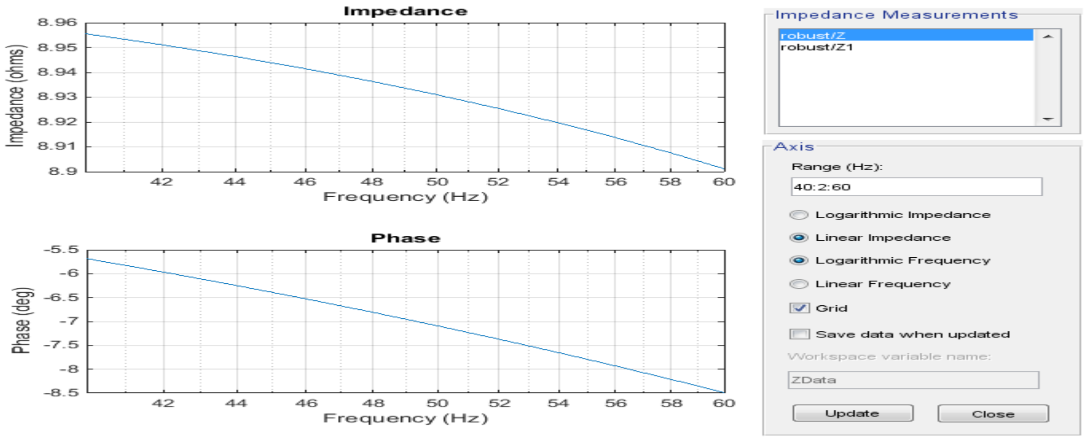


Fig.4.31: Current for robust droop controller.

4.5 Effect of frequency on impedence:

The output impedance of the inverters varies with respect to frequency in island mode. Because in island mode, the microgrid remain detach from grid. But in grid connected mode the frequency does not change as it synchronized with grid, only phase angle changed. Here the system frequency is 50HZ and impedance for system frequency for both inverters is 8.8627-1.1026i which is almost resistive.



robust/Z
robust/Z1

Range (Hz): 40:2:60

○ Logarithmic Impedance
● Linear Impedance
● Logarithmic Frequency
○ Linear Frequency
☑ Grid
☐ Save data when updated

Fig. 4.32: Frequency Vs impedance curve.

Matlab coding:

```
power_zmeter('robust')

Zdata = power_zmeter('robust',50)

Zdata =

  Blocks: {'robust/Z'  'robust/Z1'}

        Z: [8.8627 - 1.1026i 8.8627 - 1.1026i]

     Freq: 50
```

CHAPTER 05

CONCLUSION

5.1 Overview of thesis:

Our main purpose is to design a robust droop controller for accurate proportional load sharing among the parallel inverters in island operated microgrid. At first we have studied about conventional droop controller. But due limitation of conventional droop controller we proposed a controller named robust droop controller. We have observed that the voltage set point of two inverters are more accurate then they operated for same per unit impedance. The proposed droop controller was able to share the load according to the sharing ratio and considerably outperformed the conventional droop controller in terms of sharing accuracy and voltage drop.

5.2 Future work:

In our work, we have considered single phase for sharing the load among parallel operated inverter in case of both conventional and robust droop controller. We want to implement same work for three phase system in future. Moreover, in this thesis, we did not take any step to improve total harmonic distortion (THD). We also want to improve total harmonic distortion.

5.3 Limitation:

Microgrid can play vital role in the crisis of power. It is most popular technology in al over the world. But in our country has not been much familiarized with this technology. Though we were completed our thesis successfully, but we have some limitation. Such as

i. There no work has been done to avoid total harmonic distortion of the signal.

ii. We consider only linear load as a load for accurate proportional load sharing among parallel operated inverters. Non-linear load has not been considered here.

iii. The only possible error in the real power sharing comes from the error in measuring the RMS value of the load voltage.

5.4 Conclusion:

In this paper, a robust droop controller has been proposed due to the limitation of conventional droop controller. For accurate proportional load sharing, the conventional droop controller must have the same per-unit resistive output impedances and the voltage set-points. But these are not possible to meet practically. That’s why robust have been proposed to obtain accurate proportional load sharing for microgrids working in the standalone mode. This robust droop controller does not require the above two conditions to achieve accurate proportional load 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. The strategy proposed here is for inverters with resistive output impedances but it can be applied to inverters with inductive output impedances also by using different droop control method.

Refference:

[1] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, "Hierarchical Control of Droop-Controlled AC and DC Microgrids—A General Approach Toward Standardization", *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp.158 -172, 2011.

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Appendix

List of Symbols

Notation	Meaning
V	Volt
A	Ampere
H	Henry
F	Farad
HZ	Hertz
δ	Phase angle
θ	Impedance angle
AC	Alternating current
DC	Direct current
IGBT	Insulated gate bipolar transistor
THD	Total harmonic distortion
RMS	Root mean square
ω	Angular frequency
P	Real power
Q	Reactive power
E^*	Reference voltage