

AN ENHANCED REACTIVE POWER SHARING METHOD IN ISLANDED AC MICROGRID

A PROJECT REPORT

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CERTIFICATE

This is to certify that the Project report entitled ‘AN ENHANCED REACTIVE POWER SHARING METHOD IN ISLANDED AC MICROGRID’ submitted by **MS. ANISHA M**, to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Power Systems, Electrical & Electronics Engineering is a bonafide record of the project work carried out by her under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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ABSTRACT

Conventional droop control is the commonly used method for obtaining proportional sharing of real and reactive power in an autonomous microgrid. The distributed generators share power with respect to their ratings in an autonomous microgrid. By adopting conventional droop control, sharing of true power becomes equal. However, sharing of reactive power is not equal. Reason for this inequality is the resistive impedance of the feeder, unequal feeder lengths, and uneven or random distribution of load in the power system network. Unequal reactive power sharing is not acceptable as it results in heavy loading of distributed generators with small ratings. These small rated generators that are close to large loads are mostly affected. Unequal reactive power sharing also lead to uneven voltage profile, increases circulating current and cascaded tripping. Here a strategy which improves reactive power sharing and removing its dependency on communication is used. In this a nominal voltage of each VSI adjust itself thus updating the reference voltage each time further enhancing the sharing of reactive power is utilized. Significant enhancement of this wattles power is obtained compared to a strategy which use fixed nominal voltage. Also in the presence of a load locally placed the mentioned effective strategy could maintain a stable voltage along with enhancing wattles power. This method reduces the reactive power sharing error by keeping the voltage stable. The simulation of the system done through MATLAB SIMULINK.

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LIST OF SYMBOLS

ω^* = Reference frequency

ω_n = Nominal frequency

m_p = Droop slope

P_f = Filtered instantaneous active power

V_{od-r}, V_{oq-r} = dqo frame reference voltages

V_n = Nominal voltage

n_q = Droop slope

Q_f = Filtered instantaneous reactive power

α = Unit – less factor

β = Tuning parameter

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ABBREVIATIONS

RES	RENEWBLE ENERGY SOURCE
DES	DISTRIBUTED ENERGY SOURCE
VSI	VOLTAGE SOURCE INVERTER
DER	DISTRIBUTED ENERGY RESOURCES
DG	DISTRIBUTED GENERATION
STS	STATIC TRANSFER SWITCH

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

The electricity is becoming an important element of day-to-day life. The application of electrical energy varies from household, small commercial applications to large industrial applications. Therefore it is an important necessity to generate, transmit and distribute the electrical energy all over the network by adopting efficient control methods. Global warming is a critical environmental hazard which has to be given much importance as this is an era which uses a large amount of fossil fuel for energy production. Burning of fossil fuels cause depletion of ozone layer which causes global warming. As global warming is increasing it is important to adopt a cleaner fuel [1].

Several researches are done all over the world in order to discover a fuel which is clean, reliable and efficient. Due to the increasing demand of clean energy renewable forms of energy replaced the non-renewable forms of energy. This energy is known as Renewable Energy Sources (RES). Example of renewable energies are wind energy, solar energy, geothermal energy, tidal energy etc. The most commonly used are wind and solar energies. Renewable sources of energy are more compatible compared to energies like fossil fuels. Most of the non-renewable forms of energies are utilized in power plants. Power plants have the limitation of high capital cost and location. This demerit is overcome by the use of renewable energy sources.

As renewable forms are intermittent in nature it is essential to adopt efficient method for the proper utilization of renewable energy forms so that it becomes more reliable [2]. While adopting several control methods the system becomes challenging. Renewable energy sources which are included in the distribution network is called Distributed Energy Resources (DER). Several distributed energy resources combine to form a microgrid. Microgrid must procure adequate storage as well as generation capability in order to serve loads during autonomous mode of operation [3].

With the penetration of distributed generators the structure of electric grid is transformed from a single structure to different small structures. The integration of distributed generators especially in the recent times made the power sharing and control challenging. So in order to achieve an accurate sharing of the power commonly used method is controlling the droop that is P- ω and Q-V droop control. But in the conventional system by the control of droop there is an equal sharing of real power but the sharing of reactive power is unequal [4].

There are several control strategies that is being adopted to control the distribution of power between voltage source inverter in an autonomous microgrid [5]. Some control methods improve the droop slope and enhances the sharing of reactive power, but it results in unstable voltage [6]. Some techniques need an adjustment between the sharing of enhanced wattles power and voltage [8]. Using a central controller an adaptive adjustment of the droop slope can be done [7].

In some cases disturbance is injected based on change in reactive power to the P- ω droop and the integral of active power error is given to the Q-V. Thus enhances reactive power sharing. But in these cases load change during compensation affects the reactive power sharing [9]. Another control strategy is the virtual impedance method [10]. This method equalizes the feeder impedance and also changes the resistive system to inductive thus improving reactive power sharing. But if the virtual impedance is not designed properly it would result in voltage instability. This can be without [11-14] or with [15-19] communication based strategy.

In most of the control strategies a communication based system is adopted. In other methods while enhancing sharing of reactive power there will be high voltage deterioration and instability in the system. Looking into the problems mentioned a controlling strategy in relation to the self-adjusting droop is used that gives an almost accurate reactive power sharing along with a stable voltage. Adopting this control strategy the system becomes more efficient and stable.

1.2 MICRO-GRID

In the beginning the architecture of grid raised up as a structure which is centralized. But as new trends and developments were implemented the centralized form transformed to a decentralized form. The main development for the cause of this transformation is the penetration of Distributed Generators (DG). Distributed generators produce distributed energies like solar energy, combined heat and power, wind energy. It also utilized stored energy from batteries that is the energy from an Energy Storage System (ESS).

In a system having plug and play functionality the distributed generators can be easily connected as well as disconnected. This is because in plug and play model distributed sources can have a direct access of micro-grid without depending on control and protection strategies [20]. Whatever be the source in a distributed generation it needs an inverter to ensure proper control and reliability [21].

The distributed energy source inverter can be operated in three different modes. Grid-Forming mode in-order to imitate the character like amplitude and frequency of an AC source which is fixed. This is adopted in islanded micro-grids. Grid-Supporting mode which ensures the regulation of both voltage and frequency. This is for both grid connected as well as islanded mode of operation. Grid-Feeding mode puts an appropriate level of real and reactive power [22]. Distributed generators are mainly affected by the problem like integration and interfacing. Besides these issues they are also affected by system instability and inaccurate sharing of real and reactive power in the system between distributed generators [23].

Control goals of Grid-Supporting mode:

- i. Ensures that frequency and voltage are maintained at stable values.
- ii. Sufficient real and reactive sharing of power in parallel connection.

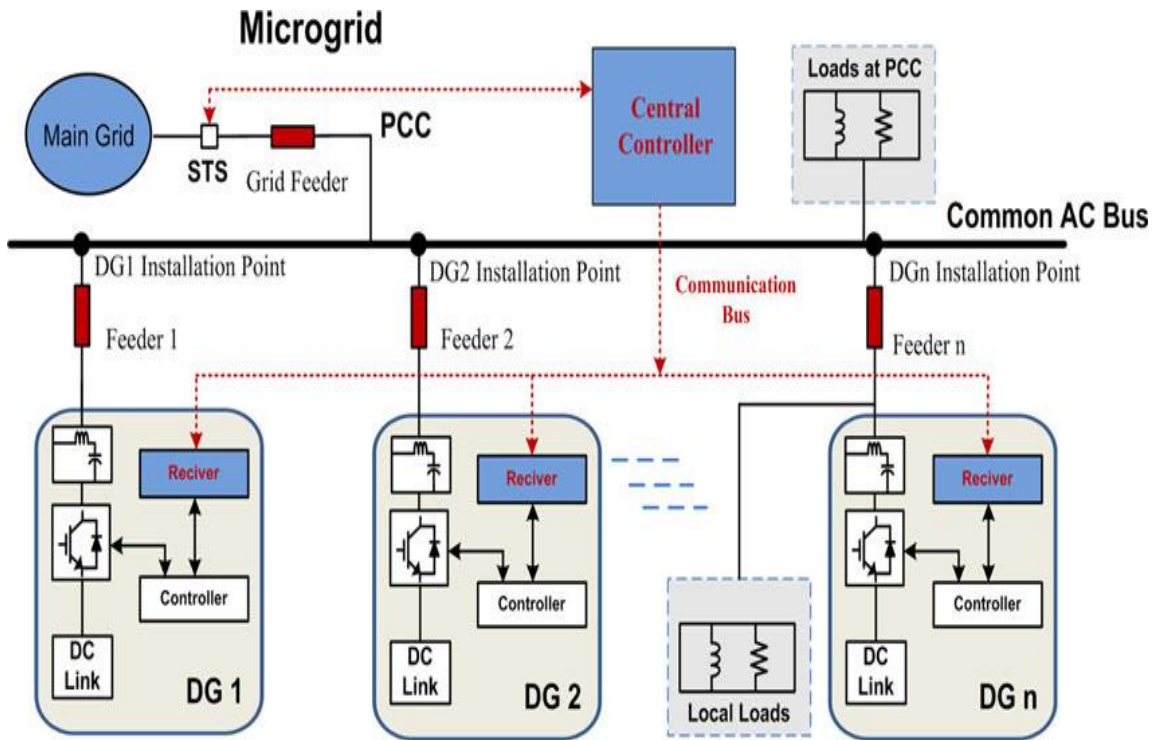


Fig.1.1 Architecture of microgrid [22].

Micro-grid can be defined as a small scale power grid which operates independently that is an islanded mode of operation or which operates in co-ordination with the main grid that is grid connected mode of operation. Micro-grids consist of a number of loads that are interconnected and various distributed generators. As these loads and distributed generators are included in a well-defined boundary it can be operated as a single entity which could be controlled. Micro-grid can be called as an energy efficient system which is self-sufficient. This is because it operates in a distinct geographic area like schools, colleges, malls, hospitals and other companies.

The control in micro-grids can be classified as primary control, secondary control and tertiary control. In primary control particular point is made fixed as a set point so that the micro-grid remains stable at these points. Also it will be within specified tolerance band. It maintains the rated frequency and voltage.

Compared to primary control of system secondary control is slower. There will be slight variations in the exact value in a primary control. These slight variations are compensated by the secondary control. The slowest control among the three control methods is the tertiary control. The tertiary control controls the real and reactive power flow between micro-grids [24,25].

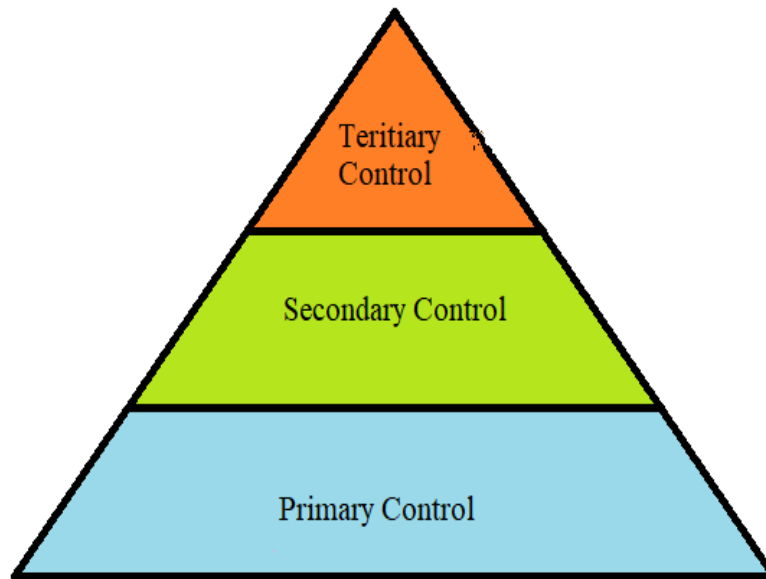


Fig.1.2 Different control levels in micro-grid

The characteristics of micro-grid can be mentioned as local, independent and as an intelligent system. In local the energy from micro-grids can be said as a local form of energy since it produces energy and serves the nearby customers. We are served with electrical energy from the large grids which is centralized. These large grids receive energy from power plants from which electricity is transmitted through long distances and distributed. In this case the efficiency decreases as power of about 9% to 16% is dissipated as it travels over long distance in lines before serving the consumers. There is a complete dependency on these large grids for electricity until the evolution of micro-grid. As micro-grids generate power close to the load center the demerit of power dissipation is solved.

Independent means a micro-grid can operate independently that is an islanded mode of operation. In this case the Static Transfer Switch (STS) is open so that the micro-grid is not connected to the main grid. Even in the case of grid failure micro-grid ensures uninterrupted supply [26]. A micro-grid is said to be intelligent especially because of its controller operation. The controller controls the generation as well as batteries. Controller operates in such a manner so as to obtain low prices, good quality energy, high electrical reliability etc.

1.3 Thesis outline

Thesis is organized as follows:

- Chapter 2: Gives the objective of thesis.
- Chapter 3: Shows the literature review done on thesis topic.
- Chapter 4: Explains the relationship between reactive power and voltage.
- Chapter 5: Covers droop control in generators.
- Chapter 6: Presents the strategy adopted to enhance the reactive power sharing.
- Chapter 7: Shows all the simulation models used in this thesis.
- Chapter 8: Gives the simulation results of the work.
- Chapter 9: Summarizes the thesis and explains the significance of thesis.
- Chapter 10: Entitled the publication done in relation to the thesis.
- Chapter 11: Presents the references used for completing the thesis.

CHAPTER 2

OBJECTIVE

- To improve the sharing of reactive power among the distributed generators connected in parallel in an autonomous AC microgrid with a non-communication based strategy.

CHAPTER 3

LITERATURE REVIEW

3.1 INTRODUCTION

This chapter explains the literature review on different methods that enhances the sharing of reactive power.

A) Reactive power control strategy adopted in low voltage microgrid.

While adopting Q-V droop control strategy there will be an unequal reactive power sharing. This is due to the drop in voltage that occurs in line impedance. Reactive power sharing can be made more accurate by including the effect of drop in line voltage to the power control scheme. In order to achieve this $\frac{\Delta E}{Q}$ slopes are added into the voltage droop control. A virtual inductor can be introduced at the DGs output. This controls the real and reactive power flow that is being decoupled as well as efficiently utilizes $\frac{\Delta E}{Q}$ slope for enhancing the wattles power sharing and control.

The $\frac{\Delta E}{Q}$ slope K_Q is incorporated for enhancing the wattles power sharing. If $\frac{\Delta E}{Q}$ slope that is K_Q is not considered then the slopes of voltage droop will be SP'_Q . This is a case of two DGs so one of the DG will generate reactive power above maximum range. If $\frac{\Delta E}{Q}$ slope K_Q is considered, the slope of voltage droop will be SP_Q . In this case the maximum reactive power will be simultaneously generated by two DGs. During this time the voltage at the point of common coupling will be minimum, E_{\min} . Therefore it is evident that by considering the $\frac{\Delta E}{Q}$ slope the operation of DGs beyond maximum limit and dropping of voltage below minimum limit can be minimized [27].

B) Reactive power sharing with unequal feeder reactance

Two DGs have separate feeder characteristics. The reactance X_1 and X_2 are not equal that is $X_1 < X_2$. Reactive power of DG_1, Q_1 is greater than reactive power Q_2 of the second distributed generator DG_2 . Eventhough deeper droop slope D^*_Q reduces the error reactive power sharing it reduces the voltage at point of common coupling (PCC). Also due to the voltage change there will be a reduction of variations in reactive power demand. So compensation methods are adopted for minimizing the reactive power sharing errors.

➤ Compensation method for reactive power sharing errors

An enhanced control strategy is adopted in this compensation. Initially the reactive power error is checked by introducing the real power disturbance. Central controller provides a synchronizing signals of lower bandwidth. This signal activates the real power disturbance that has to be injected by acting as a communication link. The communication link connects the central controller with the local controller of different DG units. Compensation signal flows only from central controller to local controller. Addition of integral term takes place at the same time inorder to avoid the errors in reactive power sharing [22].

C) Adaptive voltage droop control strategy for reactive power sharing in islanded microgrid.

Here a different strategy is adopted rather than directly controlling the inverter output voltage. In this method the slope of the voltage droop is tuned inorder to compensate the unequal voltage drop of feeder with the help of communication links. The advantages of this strategy is that eventhough if the communication is interrupted the operation will not fail as the controller uses the droop coefficient that is being tuned at the last. Also in closed loop control, communication is not used. Therefore the strategy is resistant to communication delays. An adaptive term is added to each DG units so that there will be a continuous action of all the adaptive terms which in turn reduces the effect of bus voltage in microgrid. Feeder parameter information is not needed for this strategy. Due to this reason the need of estimation algorithm is avoided and the strategy is easy to implement [17].

D) Self adjusting droop control strategy for reactive power sharing in islanded microgrid.

V_{od-r}, V_{oq-r} are the reference voltages of the d_q frame. V_{od-n} is assumed to be the nominal voltage, V_{od-m} is the self-adjusting the nominal voltage, n_q is the droop coefficient, Q_f is the reactive power that is being filtered. Reactive power sharing in conventional Q-V droop control is not equal due to unequal feeder impedance. Also it is affected by load size and location. In this strategy a term is introduced to represent the self-adjusting nominal voltage. Here the communication is avoided as the introduced self-adjusting nominal voltage is autonomously checked by the DGs. Due to the introduction of frequency variable the reference voltage of the DGs is driven thus improving the sharing of reactive power. Accurate reactive power sharing is achieved in the absence of communication needs and also avoided the need of information regarding feeder impedance [28].

E) Reactive power sharing with load detection algorithm.

In this method a compensating signal G and disturbance term $n_q Q_f$ is introduced. At the condition when the compensating signal is greater than zero the disturbance term as well as the compensating term will get activated. If there is an unequal reactive power sharing between the DGs unequal amount of offsets will be produced. These offsets are injected into $P-\omega$ droop of each DG. Due to these offsets there will be an unequal sharing of active power which causes active power sharing errors. The integral of this error improves the reactive power sharing after compensation. Load change detection algorithm is used in order to detect the load change and for starting the compensation process. This technique avoids the need of synchronizing signal from the central controller. When load change occurs it spontaneously corrects the reactive power sharing. The benefit of this load change detection algorithm is that it detects the load change even at the time of correction process [29].

CHAPTER 4

REACTIVE POWER AND VOLTAGE

4.1 Reactive power and voltage in AC system

Reactive power is also known as imaginary power. Role of reactive power is vital in AC systems. In an AC system the reactive power occurs due to the phase difference between voltage and current. The reactive power increases with increase in phase difference. Even though reactive power is not a useful one it plays a vital role in the power system as it maintains the voltage in the system which in turn helps in transmitting real power through transmission lines. Loads especially in motor loads reactive power helps to produce useful work by converting the flowing electrons. In electrical machines reactive power maintains magnetic as well as electric field.

Reactive power and voltage are proportional. When reactive power is less the voltage will reduce thus hinders the flow of active power from the generator to the load. Under this condition there will be incidents like overheated induction motors, dimming lights etc. suppose there is excess reactive power. In this condition the voltage will be high resulting in insulation failure, burn outs and damages in electrical equipment. Lack of reactive power control leads to failure of voltage which causes tripping. Tripping affects generation, transmission and distribution. A system is unstable means it could not meet its reactive power demands.

4.2 Deriving relation between voltage and reactive power

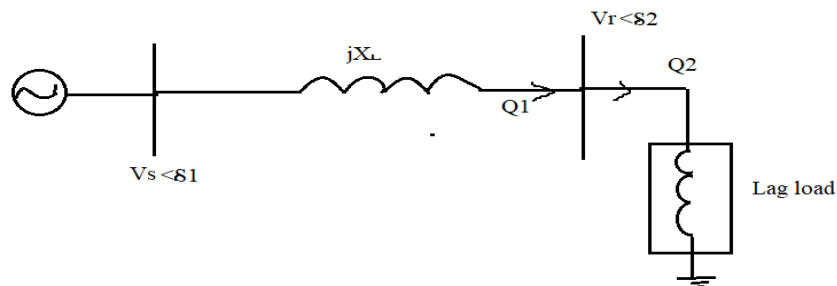


Fig.4.1 Transmission line diagram

Q_1 be the supplied reactive power and Q_2 be the reactive power demand. V_s be the supply voltage with angle δ_1 and V_r be the receiving end voltage with angle δ_2 . Let the load be lagging.

$$\text{Let } Q_R = Q_1 - Q_2 \quad (1)$$

$$Q_R = \frac{V_s V_r}{X_L} \times \cos(\delta_1 - \delta_2) - \frac{V_r^2}{X_L} \quad (2)$$

Considering the angle to be equal equation (1) becomes

$$Q_R = \frac{V_s V_r}{X_L} - \frac{V_r^2}{X_L} \quad (3)$$

$$V_r^2 - V_s V_r + Q_R X_L = 0 \quad (4)$$

$$V_r = \frac{V_s}{2} + \sqrt{\frac{V_s^2 - 4X_L Q_R}{2}} \quad (5)$$

Under case 1 consider Q_R equal to zero. This is an ideal case which is practically not present. In this case both sending and receiving end voltage becomes equal. Next case 2 is where Q_R is greater than zero which means supplied reactive power is higher than the reactive power at receiving end. Thus receiving end voltage is larger than sending end voltage. In case 3 Q_R is less than zero which means reactive power demand is higher than reactive power supplied. Thus receiving end voltage is higher than supply voltage. From this it is clear that in order to control the receiving end voltage reactive power must be controlled. Voltage becomes unstable due to disturbance, change in load etc. If the system is not able to meet its requirements of reactive power then the system is said to be unstable [30].

CHAPTER 5

DROOP CONTROL IN GENERATORS

Accurate reactive power sharing can be achieved by Q-V droop characteristic. The droop characteristic is triggered by a local decision making strategy. By doing this the need for central controller thus in turn the need for communication link is avoided. In this way communication delay can also be eliminated. In order to achieve accurate reactive power sharing several types of strategies are being adopted. For obtaining almost accurate result these strategies must adopt characteristics mentioned as:

- It should not be very intensive during computation.
- It should be easy to implement.
- Plug and play functionality must be present.
- Must react spontaneously to the load changes that takes place continuously.
- Even for a system with wide difference in feeder impedance the control strategy must function properly [28].

In a system there will be a change in frequency when load changes. If load is increased in a system then the speed of the prime mover falls which in turn reduce the frequency. Similarly when load is reduced the speed of prime mover increases which in turn increases the frequency. In power system it is essential to maintain the frequency. So by adjusting the speed the frequency can be kept constant. This can be called as speed droop control that is P- ω droop control. Similar is the case of voltage and reactive power. Consider the example where an inductive load is added to the system. Due to the addition of inductive load the consumption of reactive power increases which in turn results in a reduced reactive power supply. Thus voltage deviation occurs which makes the system unstable. Here also it becomes essential to make stable voltage. This is called voltage droop control that is Q-V droop control [31].

Speed droop control setting D_S , can be determined by the equation,

$$D_S = \frac{S_{NL} - S_{FL}}{S_{FL}} \times 100\% \quad (6)$$

D_S = Droop control setting of generator

S_{NL} = Generator no load speed

S_{FL} = Generator full load speed

Similarly, voltage droop control setting D_V , can be determined by the equation,

$$D_V = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% \quad (7)$$

D_V = Droop control setting of generator

V_{NL} = Generator no load speed

V_{FL} = Generator full load speed

5.1 P-f and Q-V droop control

- P – ω droop

This is the active power frequency droop control which maintains the frequency of the system to a stable value.

$$\omega^* = \omega_n - m_p P_f \quad (8)$$

- ω^* = Reference frequency
- ω_n = Nominal frequency
- m_p = Droop slope
- P_f = Filtered instantaneous active power

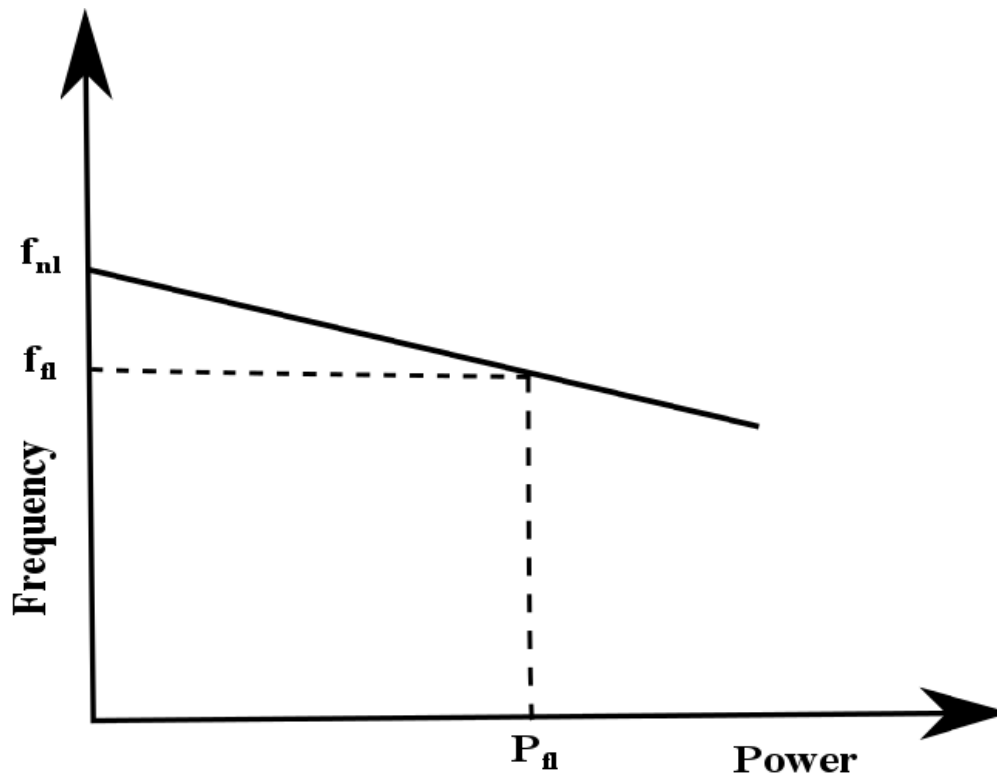


Fig.5.1 Curve of P- ω droop control [31]

- Q - V droop

This is the reactive power voltage droop control which maintains the voltage of the system to a stable value.

$$V_{od-r} = V_n - n_q Q_f \quad (9)$$

$$V_{oq-r} = 0 \quad (10)$$

- V_{od-r}, V_{oq-r} = dqo frame reference voltages
- V_n = Nominal voltage
- n_q = Droop slope
- Q_f = Filtered instantaneous reactive power

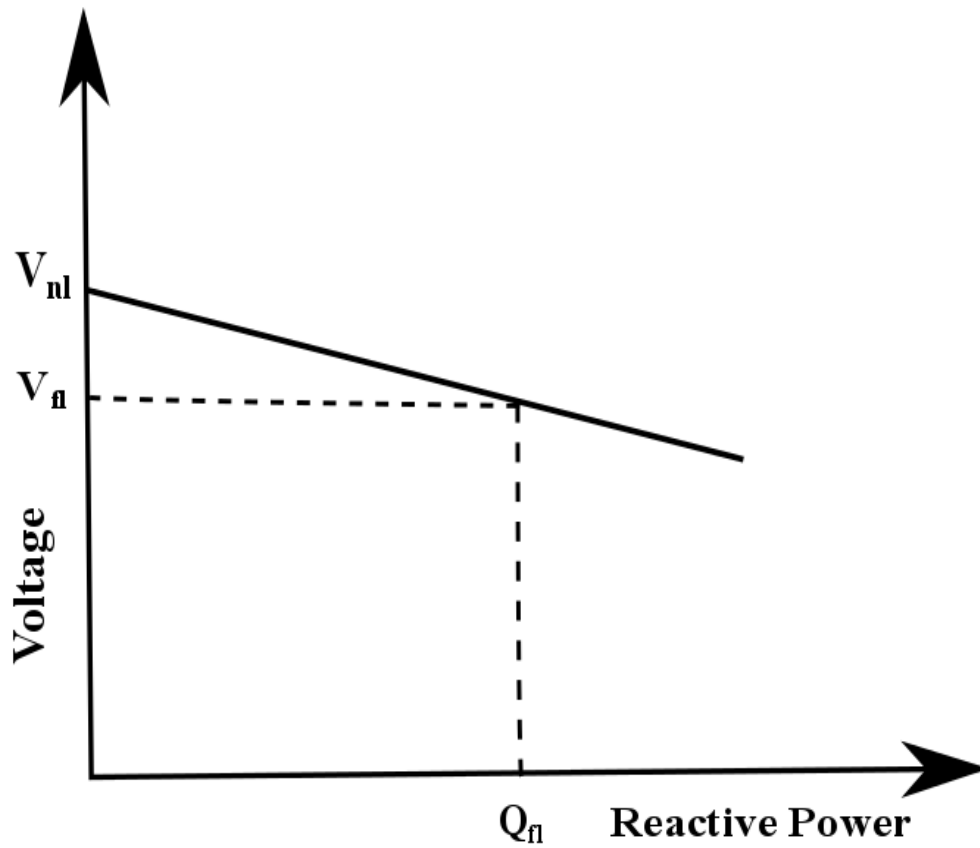


Fig.5.2 Curve of Q-V droop control [31]

5.2 Deriving P-f and Q-V droop control

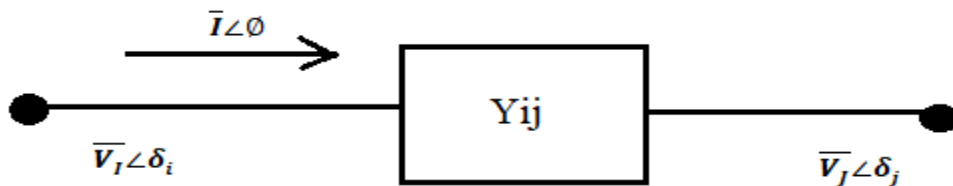


Fig.5.3 Current carrying transmission line

Total current flowing through this transmission line has both active as well as reactive power. It is shown by the equation:

$$S = P + jQ = \Delta V \cdot I^* \quad (12)$$

$$S_{ij} = V_i \cdot \left(\sum_{j=1}^N Y_{ij} \cdot V_j \right)^*$$

$$S_{ij} = V_i \angle \delta_i \cdot \sum_{j=1}^N (G_{ij} + j B_{ij})^* \cdot (V_j \angle \delta_j)^*$$

$$S_{ij} = \sum_{j=1}^N V_i \angle \delta_i \cdot (G_{ij} - j B_{ij}) \cdot (V_j \angle -\delta_j) \quad (13)$$

$$S_{ij} = \sum_{j=1}^N V_i V_j \angle (\delta_i - \delta_j) \cdot (G_{ij} - j B_{ij})$$

$$S_{ij} = \sum_{j=1}^N V_i V_j (\cos \delta_{ij} - j \sin \delta_{ij}) \cdot (G_{ij} - j B_{ij})$$

Where, $\delta_{ij} = \delta_i - \delta_j$

- The real part is the active power given by:

$$P_{ij} = \sum_{j=1}^N V_i V_j (G_{ij} \cos \delta_{ij} + B_{ij} j \sin \delta_{ij}) \quad (14)$$

- The imaginary part is the reactive power given by:

$$Q_{ij} = \sum_{j=1}^N V_i V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \quad (15)$$

Considering small deviations in the angle, it is assumed $\sin \delta \cong \delta$ and $\cos \delta \cong 1$. Therefore the active and reactive power equations can be written as :

$$\delta_{ij} \cong \frac{P_{ij}}{V_i V_j B_{ij}} - \frac{G_{ij}}{B_{ij}} \quad (16)$$

$$V_i V_j \cong \frac{Q_{ij}}{(G_{ij} - B_{ij} \cdot \delta_{ij})} \quad (17)$$

From the above equations it is clear that the active power and power angle are interrelated. This power angle deviates with change in time and when this power angle is divided by the term 2π the frequency can be calculated. Similar is the case of reactive power. From the equation the reactive power depends on the voltages. The dependency of active power and frequency is termed as P- ω droop control. Similarly the dependency of voltage and reactive power is termed as Q-V droop control.

5.3 Droop coefficient (n_q) and reactive power (Q)

Droop slope is the slope made by the droop curve. The effect of droop curve on reactive power sharing can be understood by the following figure:

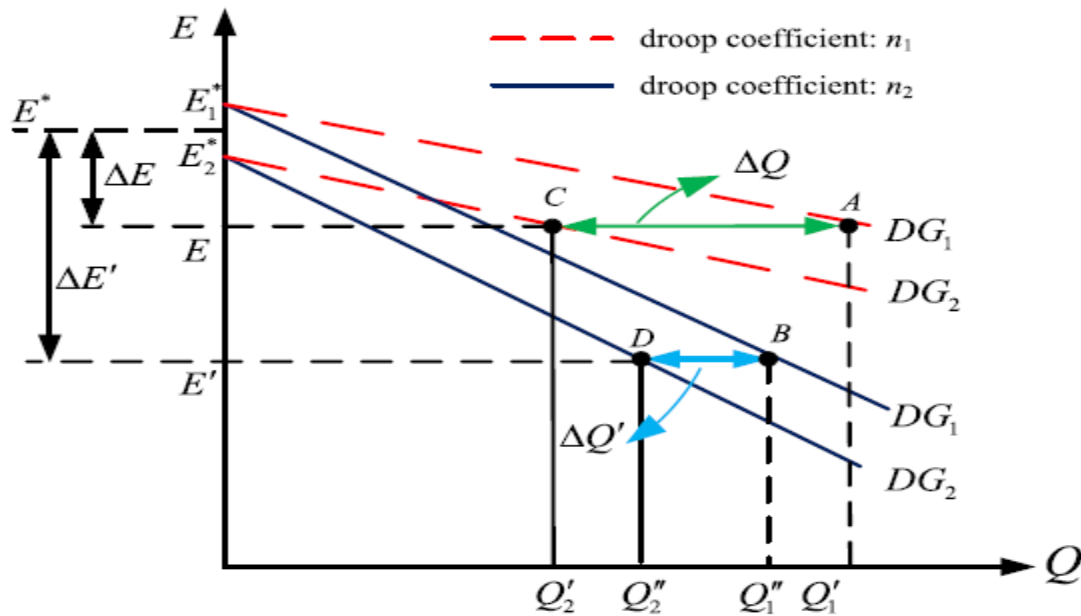


Fig.5.4 Curves showing the effect of enhanced droop slope on reactive power [26]

Slope is the ratio of rise time divided by the run time. In the figure two droop coefficients are shown n_1 and n_2 . From the figure it is clear that n_2 is having a higher slope than n_1 . Q_1' and Q_2' are the reactive powers of DG1 and DG2 having a droop coefficient of n_1 . Q_1'' and Q_2'' are the reactive powers of DG1 and DG2 having a droop coefficient of n_2 . In the figure it is evident that the system with a larger droop slope that is n_2 is having smallest reactive power deviation compared to the system with larger droop slope that is n_1 .

CHAPTER 6

SELF ADJUSTING DROOP CONTROL STRATEGY

There are several strategies which are adopted to improve the reactive power sharing in islanded microgrid. But many of these have some demerits even though they reduce the reactive power sharing error. These demerits are high system instability, deviation in voltage etc. So we have to adopt methods which maintains the stability of the system without compromising the system voltage stability. For this reason we look into a self adjusted droop control technique which reduces the reactive power deviation by maintaining a stable voltage [28]. Fig.7. shows two parallel voltage source inverter feeding a common load.

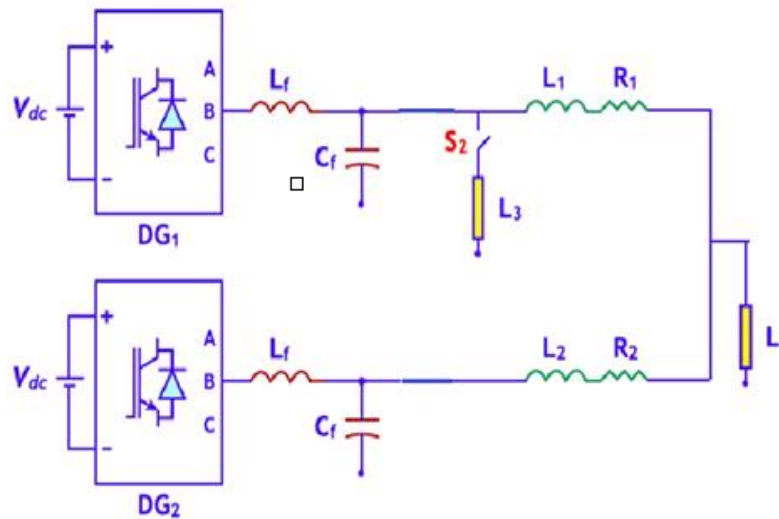


Fig.6.1 AC microgrid with two DGs [29]

6.1 Control structure

➤ CONVENTIONAL DROOP CONTROL

- P – ω droop

$$\omega^* = \omega_n - m_p P_f \quad (18)$$

- Q - V droop

$$V_{od-r} = V_n - n_q Q_f \quad (19)$$

$$V_{oq-r} = 0 \quad (20)$$

➤ MODIFIED DROOP CONTROL

- P - ω droop

$$\omega^* = \omega_n - m_p P_f \quad (21)$$

- Q - V droop

Replacing nominal voltage V_n in eq (2) with V_{od-m} adaptive nominal voltage

$$V_{od-r} = V_{od-m} - n_q Q_f \quad (22)$$

$$V_{oq-r} = 0 \quad (23)$$

- Modified droop

$$V_{od-m} = \alpha V_{od-n} \quad (24)$$

$$\alpha = \frac{\beta + V_{od-r(pu)}}{\beta + \omega_{r(pu)}} \quad (25)$$

$$V_{od-r(pu)} = \frac{V_{od-r}}{V_{od-n}} \quad (26)$$

$$\omega_{r(pu)} = \frac{\omega_r}{\omega_n} \quad (27)$$

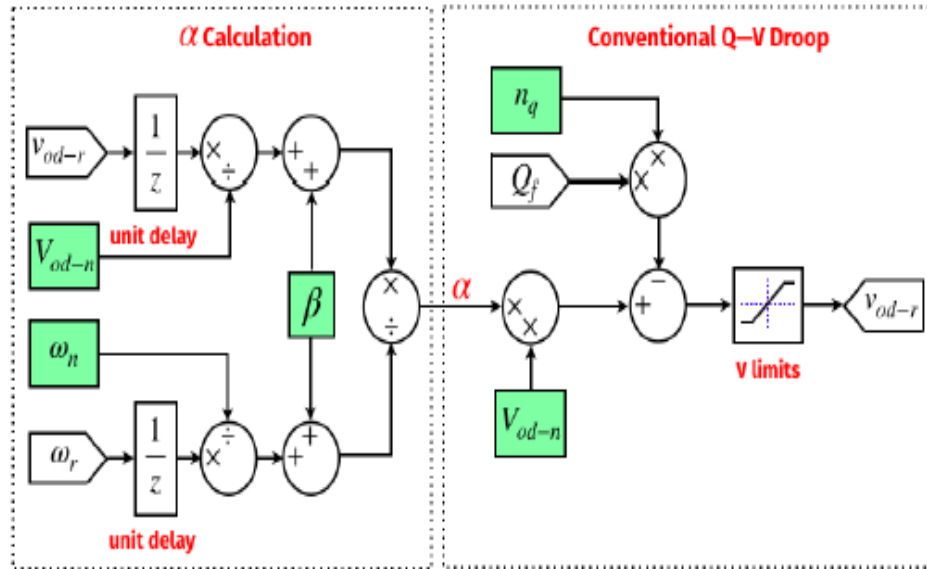


Fig.6.2 Modified droop controller [28]

The Fig.9. shows a single three phase standalone voltage source inverter feeding a common load. It has droop control as well as dual loop control. Dual loop control means it has both voltage control and current control. In a voltage control it controls the capacitor voltage through capacitor current. In current control it controls the inductor current through inductor voltage.

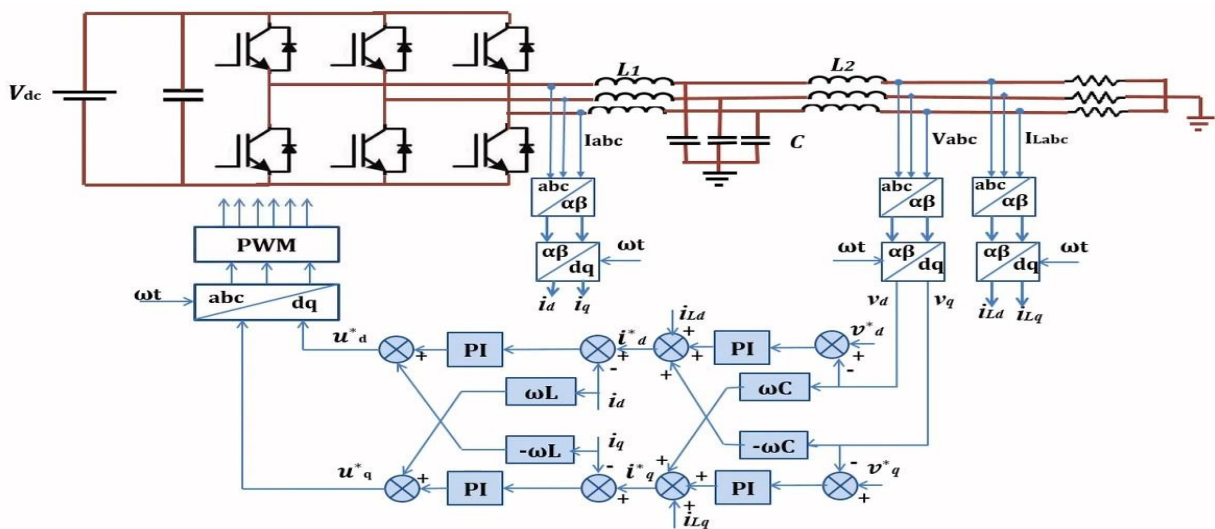


Fig.6.3 Structure of 3-phase standalone inverter

6.2 Designing of current and voltage controller

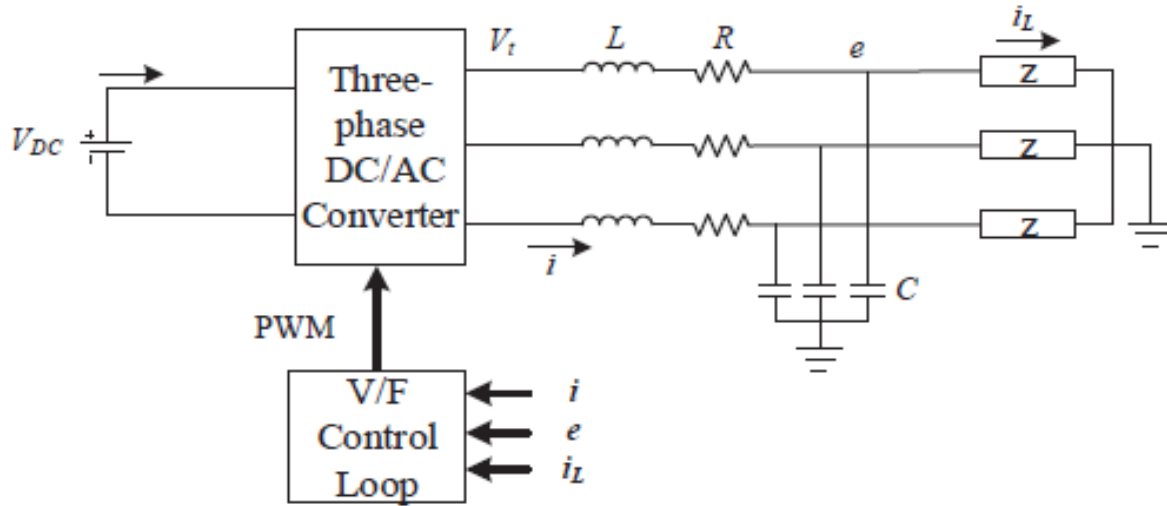


Fig.6.4 Microgrid with a VSC serving a load [32]

❖ DESIGN OF CURRENT CONTROLLER

➤ By applying KVL,

$$L \frac{di}{dt} + Ri = V_t - e, \text{ abc frame} \quad (28)$$

➤ Converting to dqo reference frame and separating equation into dq-axis

$$L \frac{di_d}{dt} + Ri_d = V_{td} - e_d + \omega Li_q \quad (29)$$

$$L \frac{di_q}{dt} + Ri_q = V_{tq} - e_q - \omega Li_d \quad (30)$$

➤ From equations (29) and (30)

$$u_d = V_{td} - e_d + \omega Li_q \quad (31)$$

$$u_q = V_{tq} - e_q - \omega Li_d \quad (32)$$

➤ The converter dq-axis reference voltages V_{td}^* and V_{tq}^* are ,

$$V_{td}^* = u_d + e_d - \omega L i_q \quad (33)$$

$$V_{tq}^* = u_q + e_q + \omega L i_d \quad (34)$$

❖ DESIGN OF VOLTAGE CONTROLLER

➤ By applying KCL,

$$C \frac{de}{dt} = i - i_L , \text{ abc frame} \quad (35)$$

➤ Converting to dqo reference frame and separating equation into dq-axis

$$C \frac{de_d}{dt} = i_d - i_{Ld} + \omega C e_q \quad (36)$$

$$C \frac{de_q}{dt} = i_q - i_{Lq} - \omega C e_d \quad (37)$$

➤ From equation (26) and (27)

$$u_d = i_d - i_{Ld} + \omega C e_q \quad (38)$$

$$u_q = i_q - i_{Lq} - \omega C e_d \quad (39)$$

➤ Reference current i_d^* and i_q^* are ;

$$i_d^* = u_d + i_{Ld} - \omega C e_q \quad (40)$$

$$i_q^* = u_q + i_{Lq} + \omega C e_d \quad (41)$$

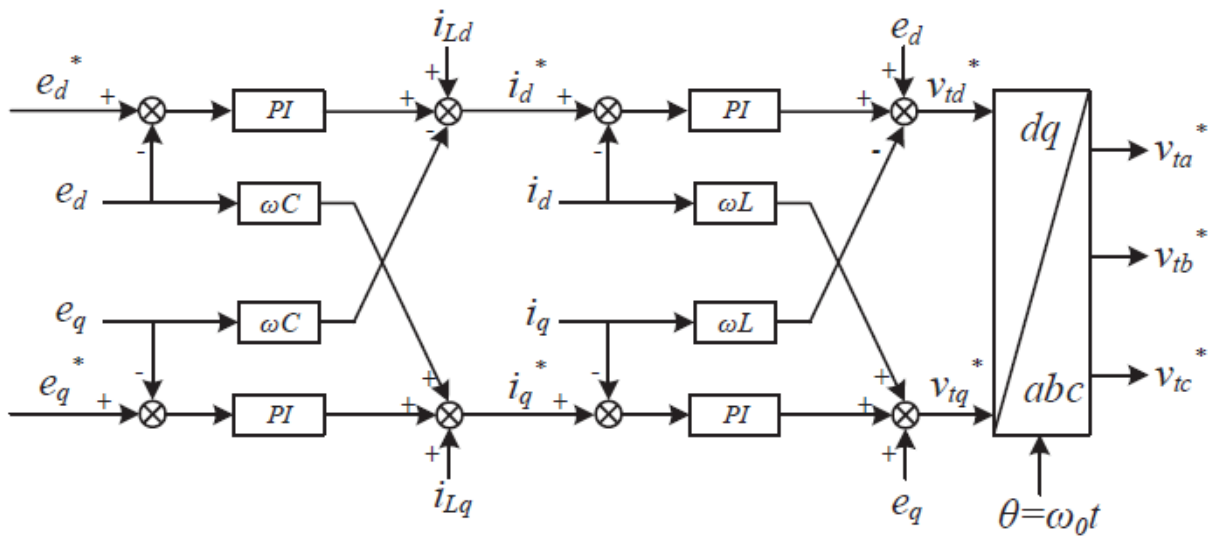


Fig.6.5 Control structure [32]

CHAPTER 7

SIMULATION MODELS

A simulation model is implemented to identify the effect of adverse parameters like unequal feeder impedance and local load which affects the proper sharing of reactive power. Fig.7.1 shows two VSI connected in parallel feeding a common load. A local load is introduced near VSI-1. The simulation models include inner current controller, outer voltage controller and droop equation of active and reactive power.

7.1 Simulation model of two VSI connected in parallel

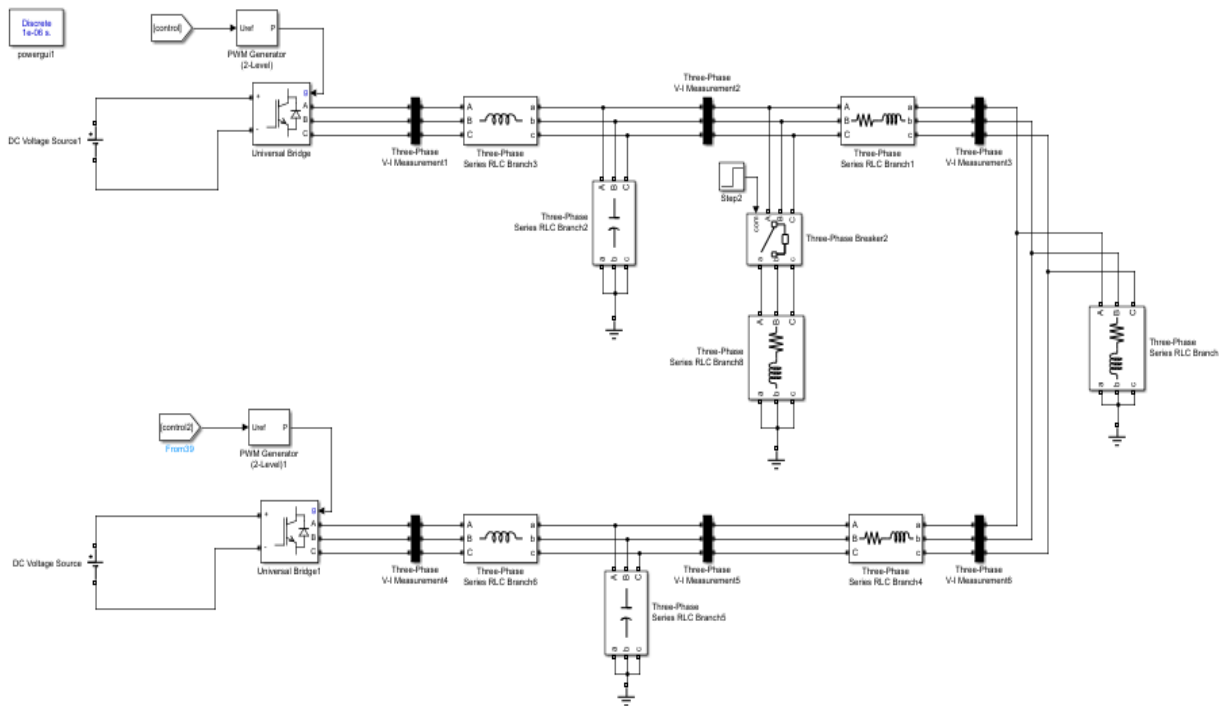


Fig.7.1 Simulation model of two VSI connected in parallel

Fig.7.2 shows the calculation of theta which is needed for dqo transformation. Fig.7.4 shows the transformation of voltage and current to dqo reference frame using theta. In Fig.7.3 voltage reference is obtained which is given to the voltage controller as input.

7.2 Calculation of theta (DG1)

➤ θ is the reference angle for dqo transformation

➤ $\omega^* = \omega_n - m_p P_f$

➤ $\theta = \int \omega^*$

➤ $\omega_n = 2\pi f$

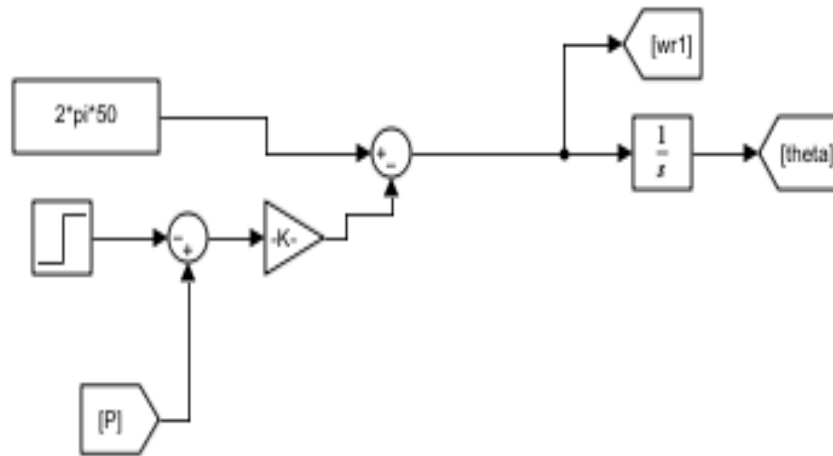


Fig.7.2 Calculation of theta

7.3 Calculation of e_{ref} (DG1)

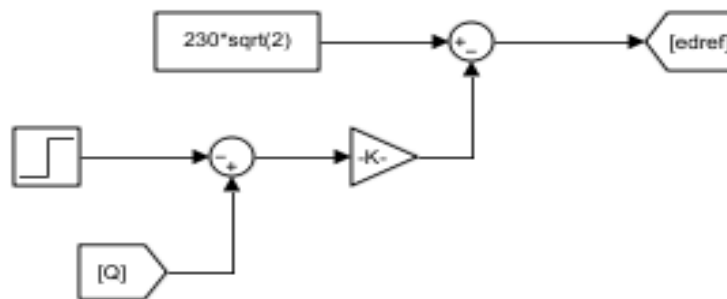


Fig.7.3 Calculation of e_{ref}

- $V_{od-r} = V_n - n_q Q_f$
- $V_{od-r} = e d_{ref}$
- $V_n = 230\sqrt{2}$

7.4 Transformation from abc to dqo reference frame (DG1)

The load voltage and inverter output current is transformed from abc to dq frame. This makes the computation easy as stationary abc frame is transformed into rotating reference frame. In this separate control of active that is d-axis as well as reactive that is q-axis of currents are possible.

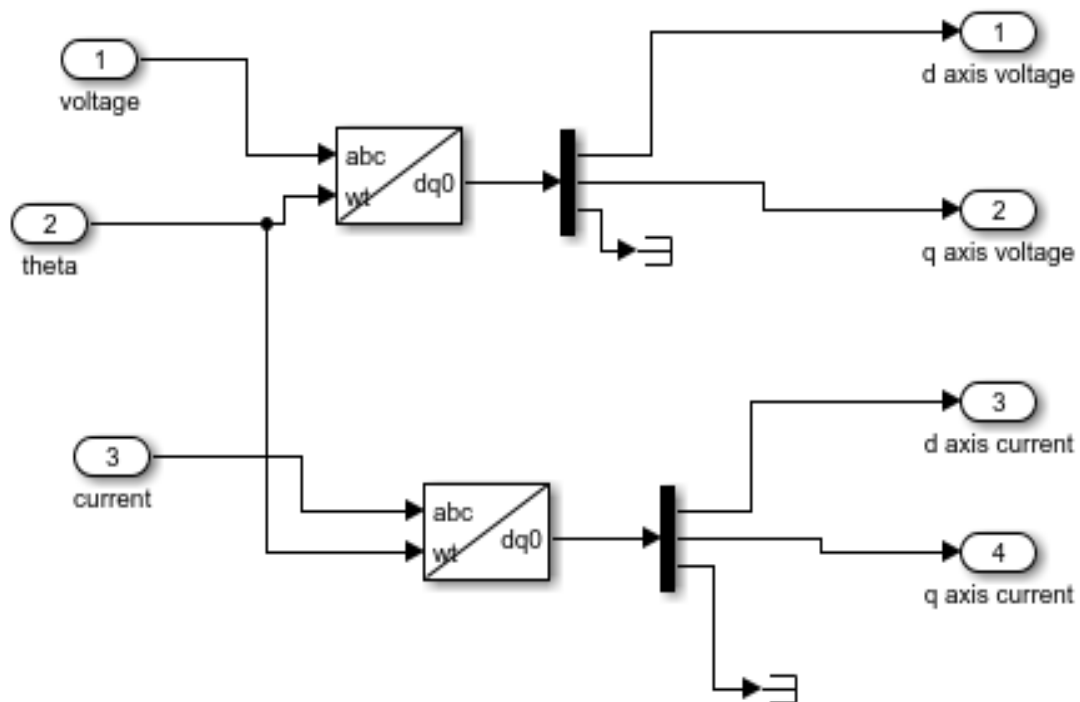


Fig.7.4 Transformation from abc to dqo reference frame

7.5 Outer voltage control loop (DG1)

- The voltage controller in Fig.7.5 has slower response than a current controller.
- Controls the capacitor voltage through capacitor current
- Has cross coupling and feed forward terms

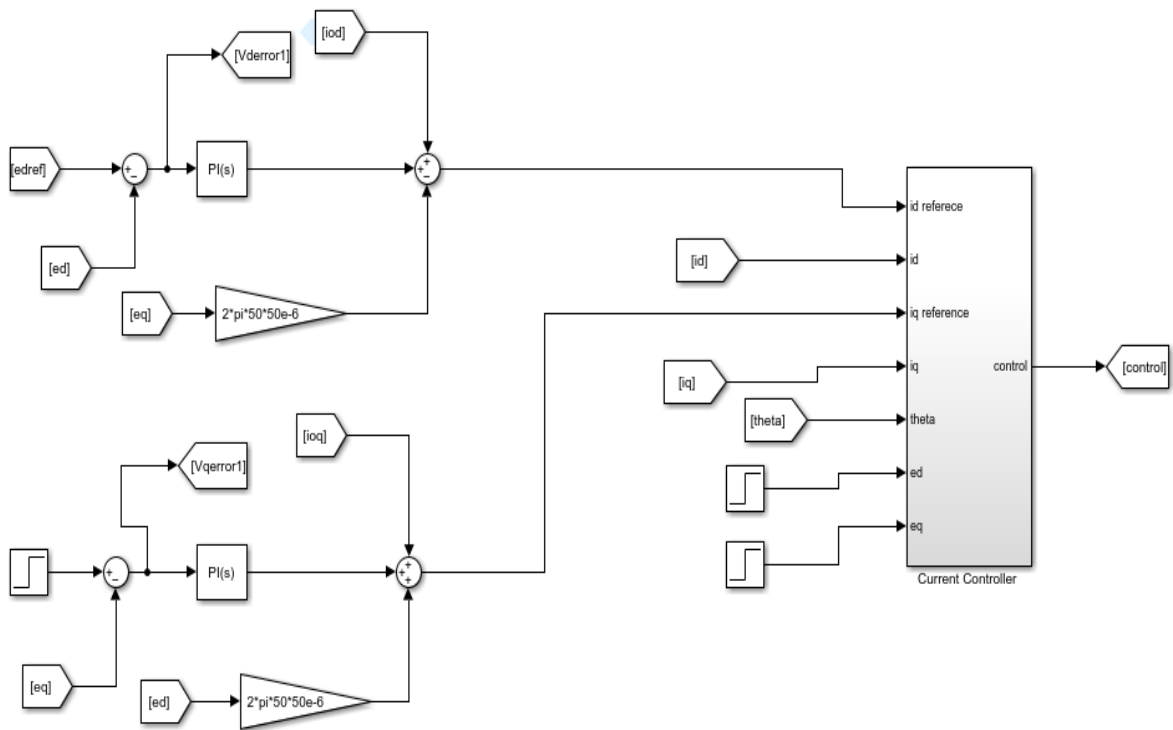


Fig.7.5 Outer voltage control loop

In Fig.7.5 and 7.6 feed forward terms as well as cross coupling terms are used in order to generate corresponding dqo components. ωL is the cross coupling term used in current controller. ωC is the cross coupling term used in voltage controller.

7.6 Inner current control loop (DG1)

- Has faster response.
- Control inductor current through inductor voltage.
- Current controller in Fig.7.6 protects the voltage source inverter from overcurrents. The voltage source inverters are prone to large currents. For this reason current control is kept as inner loop control.

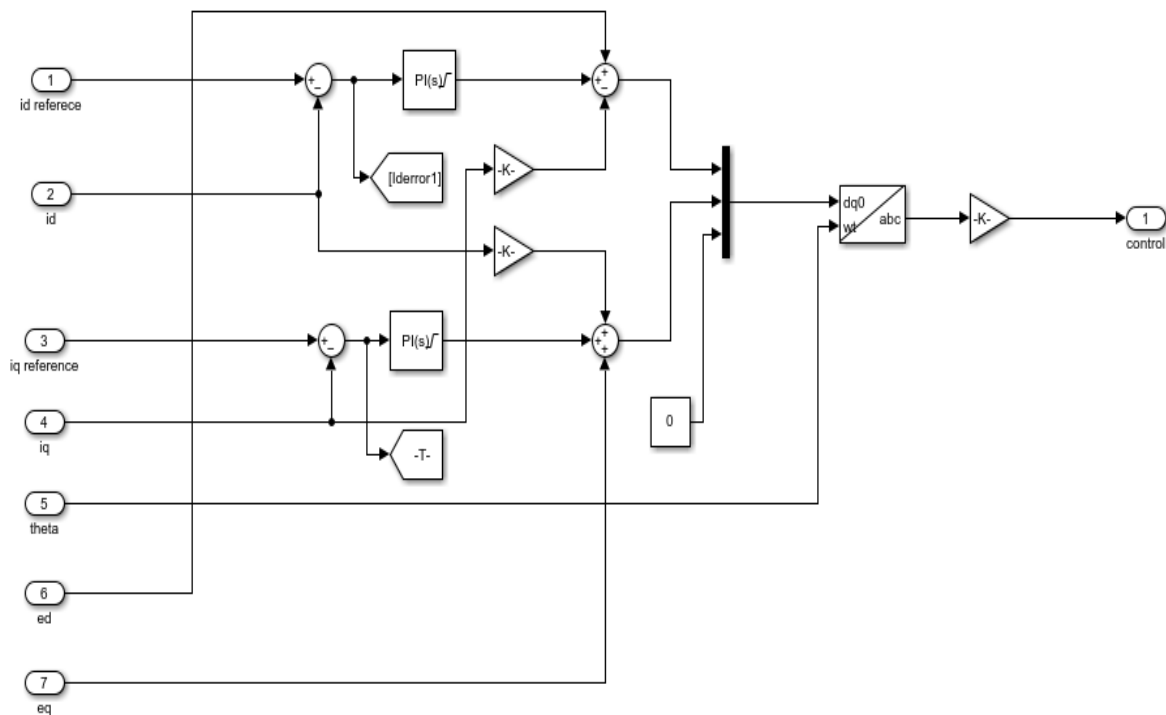


Fig.7.6 Inner current control loop

7.7 Active power calculation (DG1)

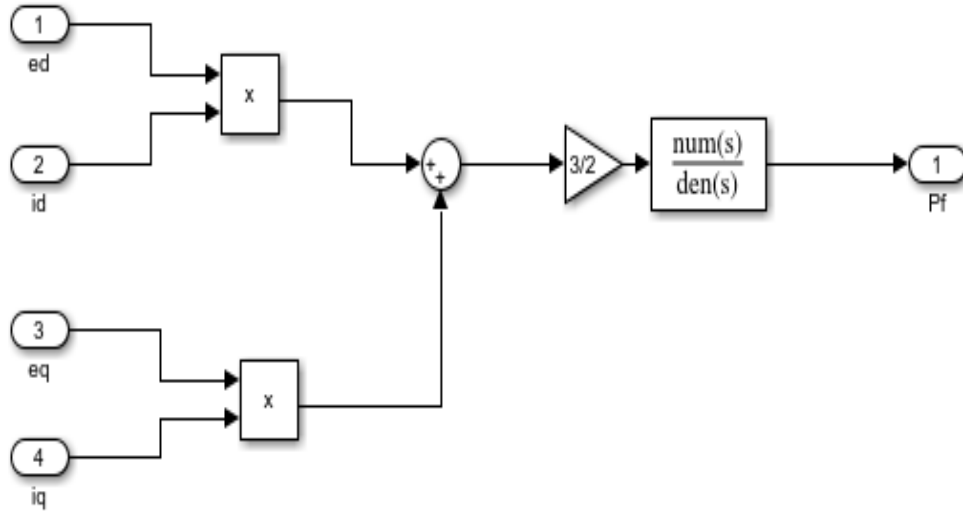


Fig.7.7 Active power calculation

$$\triangleright P_f = \frac{\text{num}}{\text{den}} = \frac{\omega_c}{s + \omega_c} * P$$

$$\triangleright P = \frac{3}{2} (e_d i_d + e_q i_q)$$

7.8 Reactive power calculation (DG1)

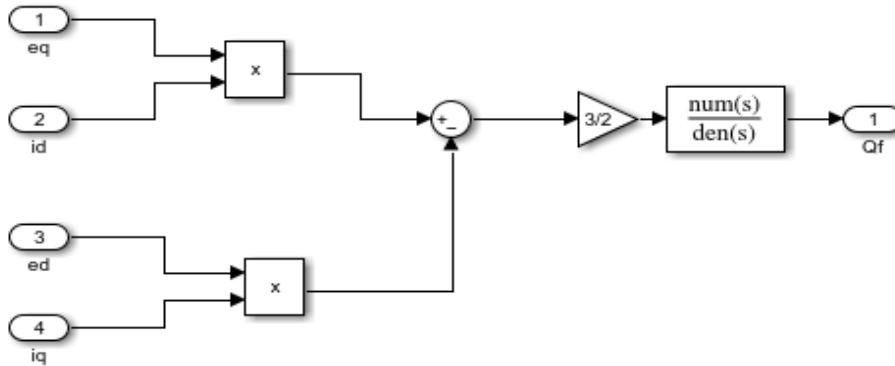


Fig.7.8 Reactive power calculation

$$\text{➤ } Q_f = \frac{\text{num}}{\text{den}} = \frac{\omega_c}{s + \omega_c} * Q$$

$$\text{➤ } Q = \frac{3}{2} (e_q i_d - e_d i_q)$$

Fig7.7 and 7.8 shows the generation of active and reactive power so that these powers can be introduced in the two droop controls which are used for controlling real and reactive powers. The output powers are passed through a low pass filter.

7.9 α calculation (DG1 & DG2)

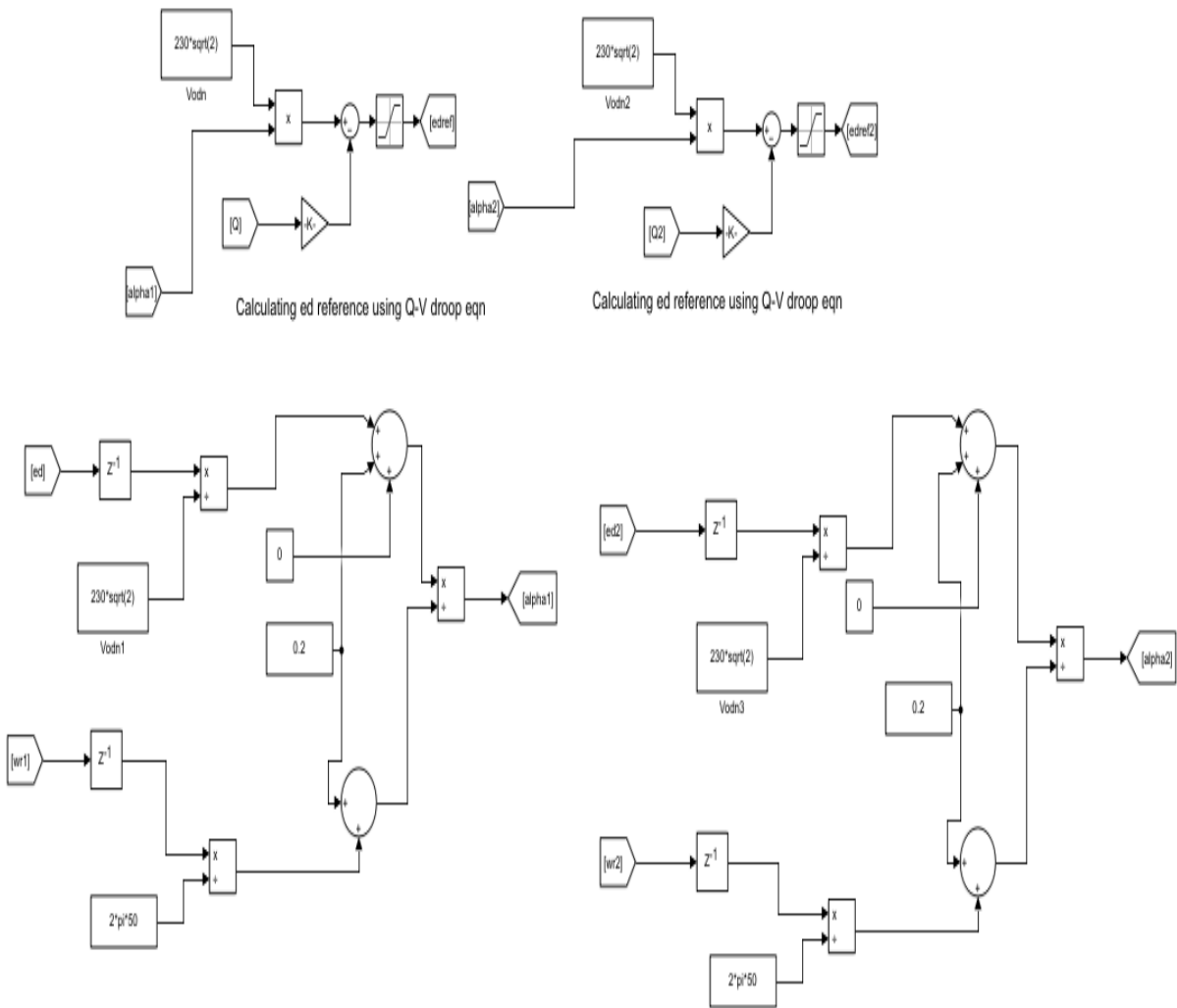


Fig.7.9 α calculation

- $V_{od-m} = \alpha V_{od-n}$
- $\alpha = \frac{\beta + V_{od-r(pu)}}{\beta + \omega_r(pu)}$
- $V_{od-r(pu)} = \frac{V_{od-r}}{V_{od-n}}$
- $\omega_r(pu) = \frac{\omega_r}{\omega_n}$

Based on the above equations from chapter 6 simulation diagram is implemented for both the distribution generators to determine the value of alpha so that it could be used in order to adjust the voltage itself in the Q-V droop thus updating the reference voltage. This simulation model is shown in Fig.7.9.

Table.7.1 Simulation Parameters

Parameters	Specifications
Vdc	800V
L	3mH
C	50F
R1	1Ω
L1	1mH
R2	1.25Ω
L2	1.25mH
Switching frequency	10kHz
Common Load	25Ω, 10mH
Local load	100Ω, 40mH
mp	2e-5 rad/s/W
nq	1e-3 V/VAR
Outer Voltage Controller	Kpv=0.1, Kiv=0.1
Inner Current Controller	Kpc=100, Kic=5000

CHAPTER 8

SIMULATION RESULTS

The simulation was done for two parallel connected voltage source feeding a common load in MATLAB SIMULINK. Here the simulation is done under the case studies using the parameters which affect the accurate reactive power sharing like unequal feeder impedance and presence of local load. Here the comparison of three different systems are done which are the conventional system, the base system and the modified system. The three systems with which the case studies mentioned below is conducted are conventional system, base model were a self-adjusting voltage strategy is implemented and modified system which is obtained by the modification of Q-V droop in the base model. The different case studies conducted for all the three systems are:

1. Equal feeder impedance
2. Unequal feeder impedance
3. Unequal feeder impedance and local load

8.1 Voltages and currents of three systems

➤ CONVENTIONAL SYSTEM

➤ PCC voltage

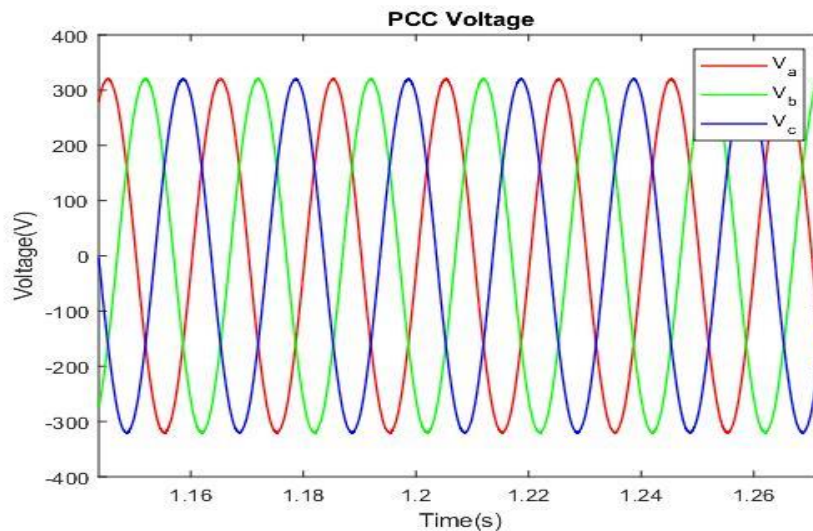


Fig.8.1 Conventional system voltage at point of common coupling

➤ Output current of VSI-1

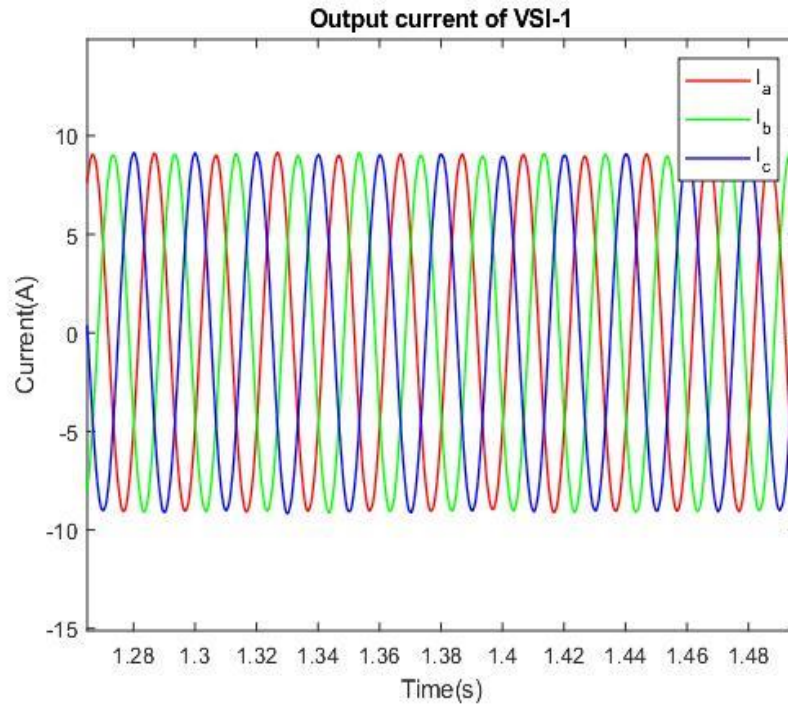


Fig.8.2 Current output of VSI-1 in conventional system

➤ Output current of VSI-2

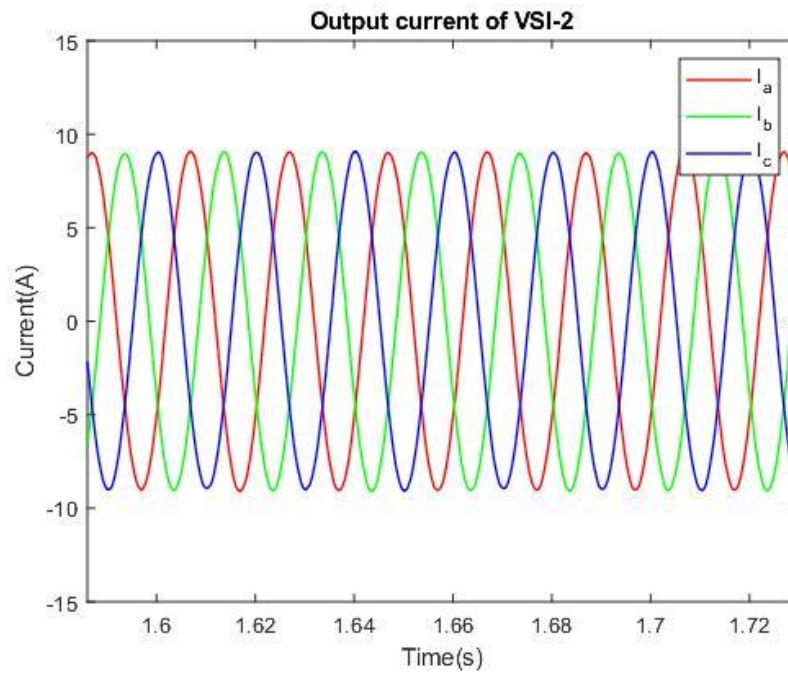


Fig.8.3 Current output of VSI-2 in conventional system

➤ **BASE MODEL**

➤ PCC voltage

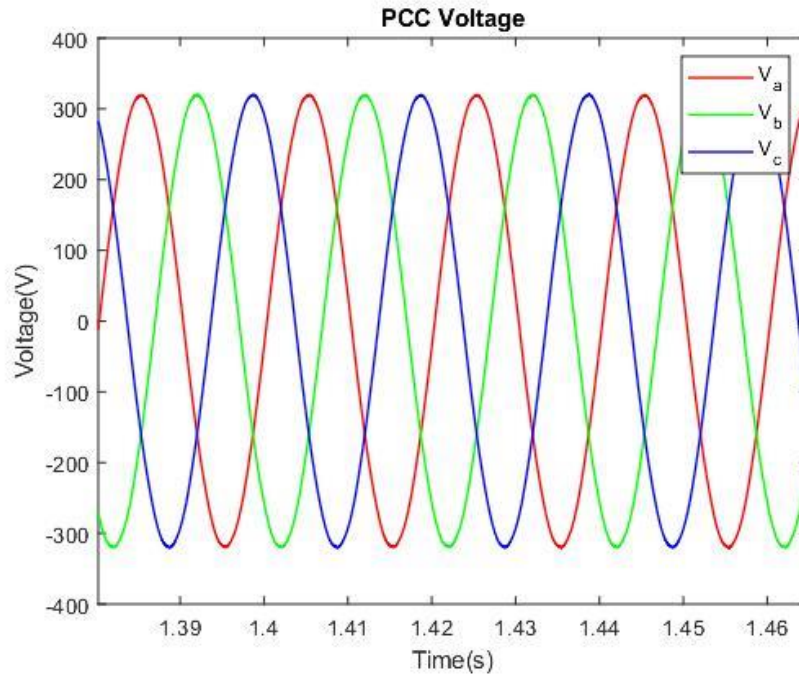


Fig.8.4 Voltage at point of common coupling in base model

➤ Output current of VSI-1

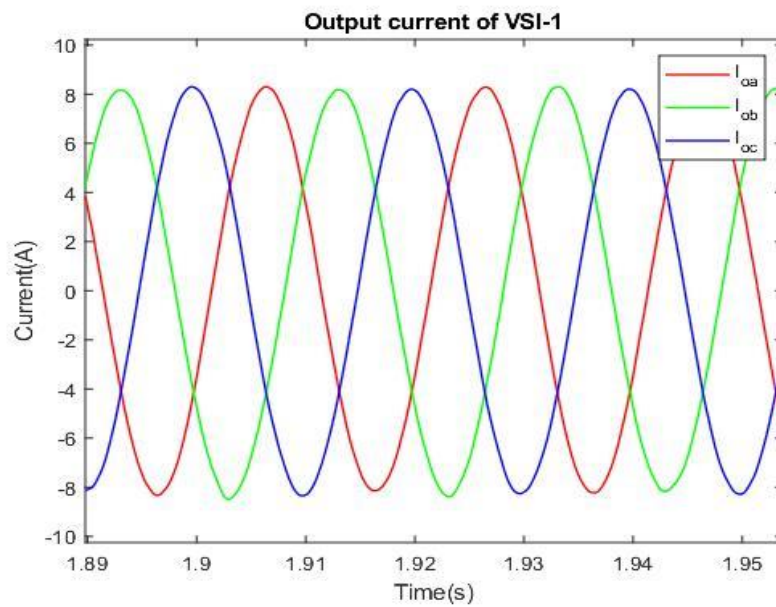


Fig.8.5 Current output of VSI-1 in base model

➤ Output current of VSI-2

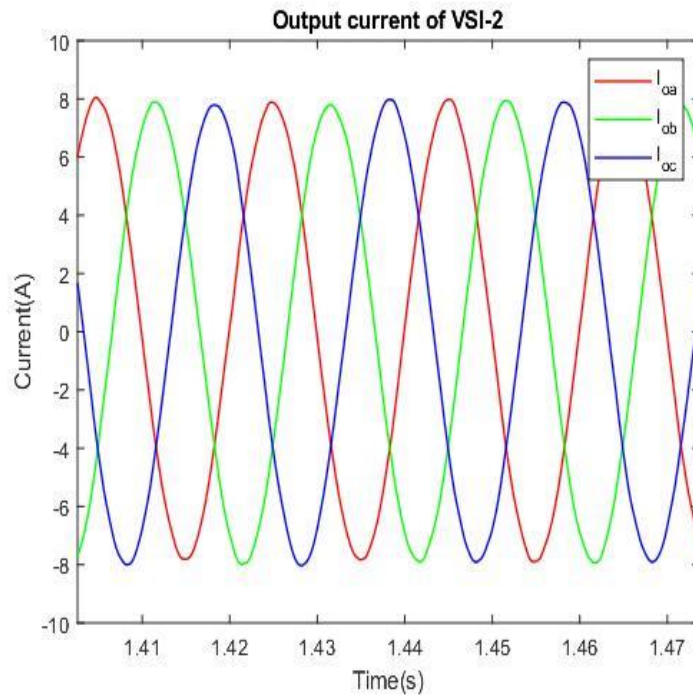


Fig.8.6 Current output of VSI-2 in base model

➤ **MODIFIED SYSTEM**

➤ PCC voltage

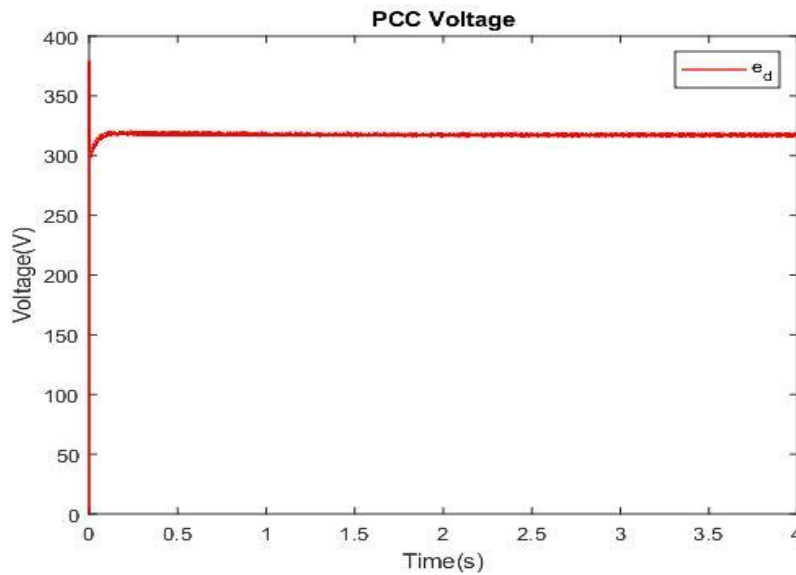


Fig.8.7 Voltage at point of common coupling in modified system

➤ Output current of VSI-1

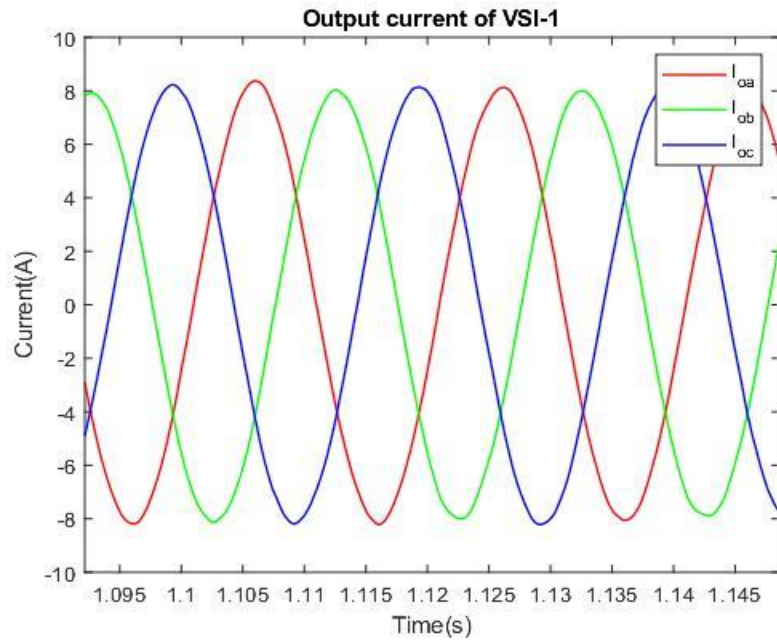


Fig.8.8 Current output of VSI-1 in modified system

➤ Output current of VSI-2

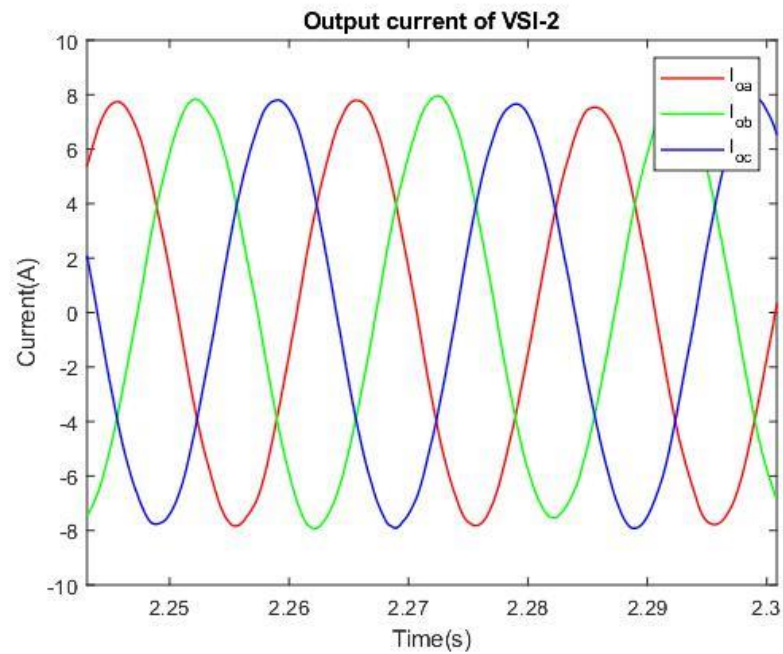


Fig.8.9 Current output of VSI-2 in modified system

From Fig.8.1 to Fig.8.9 the voltages and currents of different systems that is conventional system, base model and modified system is obtained and found that in all three systems voltage is maintained to a stable value eventhough the control strategy to enhance reactive power is introduced.

8.2 Active and Reactive power under three case studies for three systems

❖ CASE-1: WITH EQUAL FEEDER IMPEDANCE

Here an equal feeder impedance of 1Ω , 1mH is given for feeders of both VSI. Then this condition is checked and result plotted for conventional system Fig.8.10 & Fig.8.11, base model Fig.8.12 & Fig.8.13 and modified system Fig.8.14 & Fig.8.15.

1) CONVENTIONAL SYSTEM

- Active power sharing

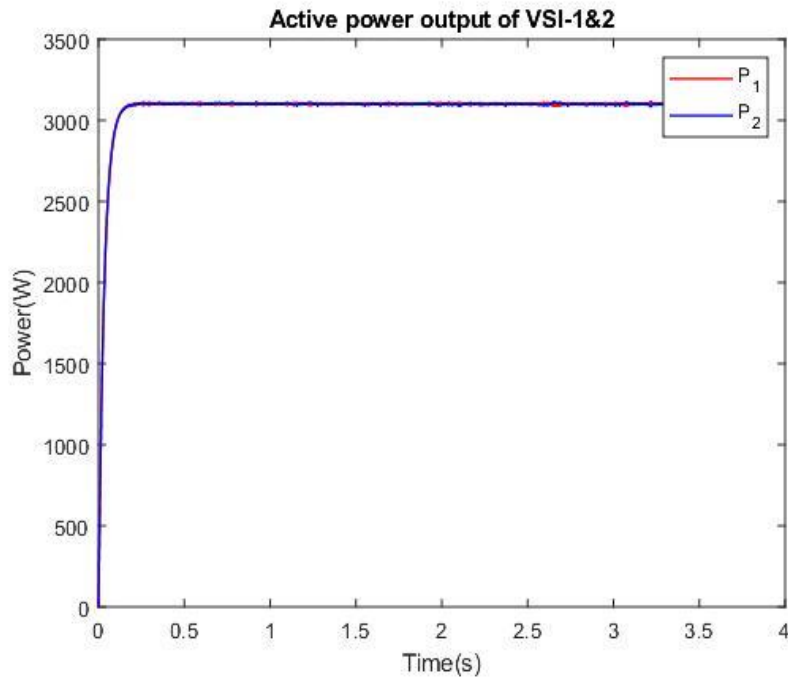


Fig.8.10 Sharing of active power in conventional system (Csa-e-1)

- Reactive power sharing

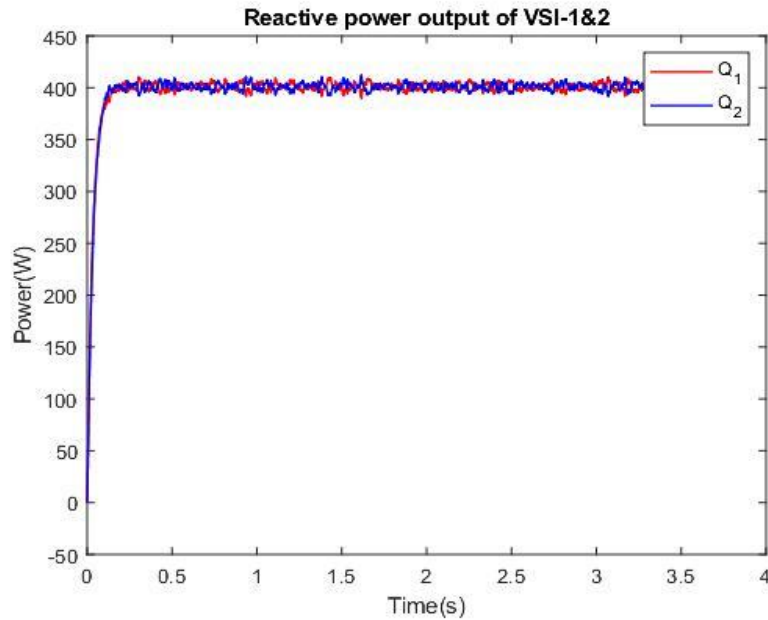


Fig.8.11 Sharing of reactive power in conventional system (Csaе-1)

2) BASE MODEL

- Active power sharing

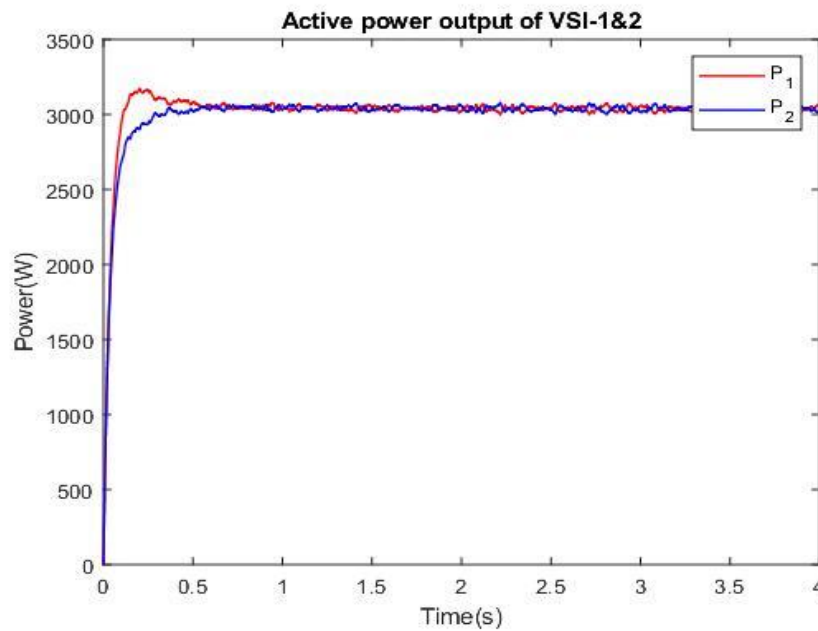


Fig.8.12 Sharing of active power in base model (Case-1)

- Reactive power sharing

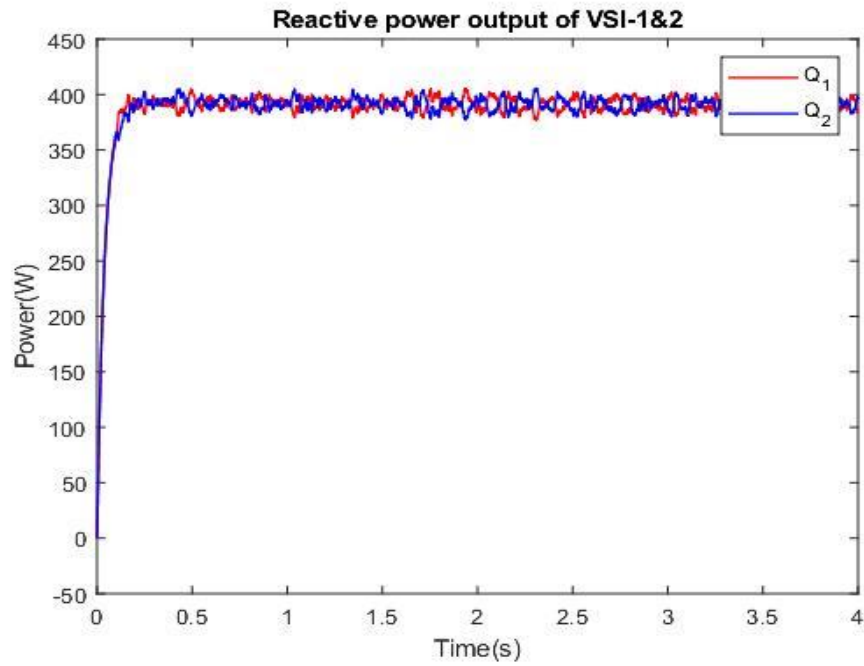


Fig.8.13 Sharing of reactive power in base model (Case-1)

3) MODIFIED SYSTEM

- Active power sharing

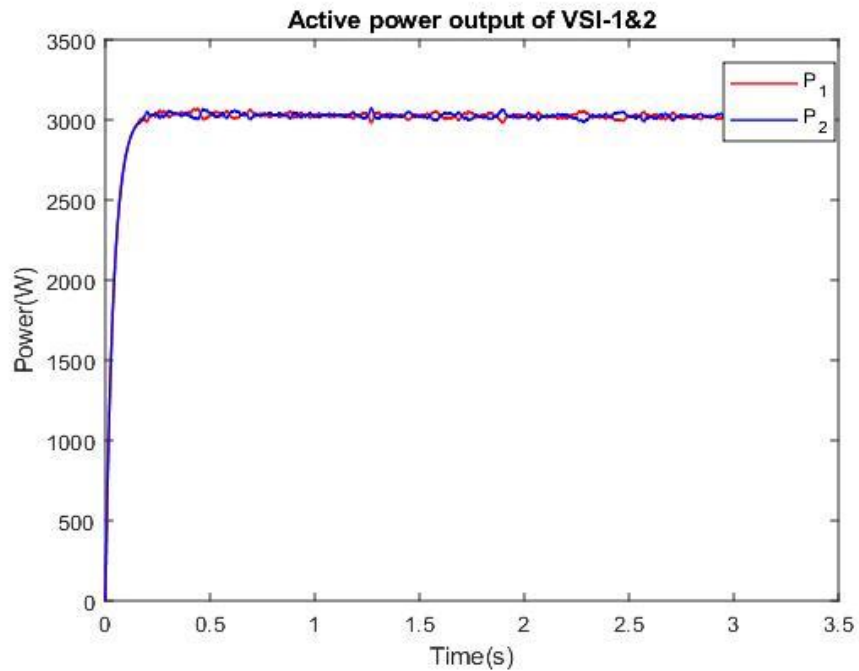


Fig.8.14 Sharing of active power in modified system (Case-1)

- Reactive power sharing

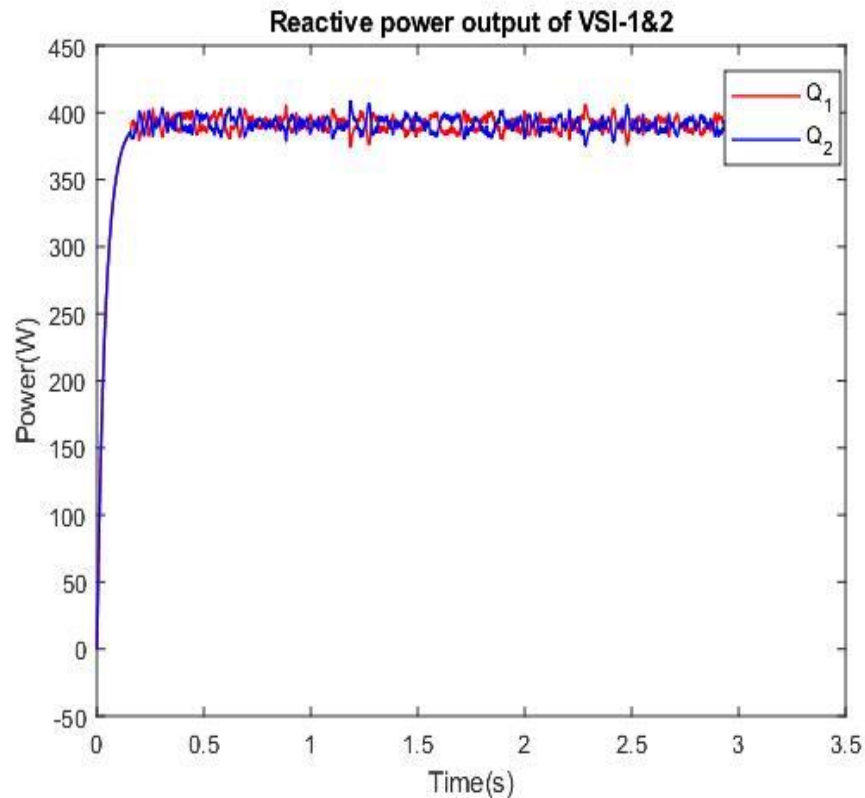


Fig.8.15 Sharing of reactive power in modified system (Case-1)

From the comparative study done on MATLAB SIMULINK at Case-1 that is under equal feeder impedance it is obtained that the reactive power and the active power is shared equally in conventional system, base model and modifies system.

❖ CASE-2: WITH UNEQUAL FEEDER IMPEDANCE

Here an unequal feeder impedance of 1Ω , 1mH for feeder of VSI-1 and 1.25Ω , 1.25mH for feeder of VSI-2 is given. Then this condition is checked for active power sharing and result is plotted in conventional system shown in Fig.8.16, base model shown in Fig.8.17 and modified system shown in Fig.8.18. The comparative plot for reactive power sharing is shown in Fig.8.19.

1) CONVENTIONAL SYSTEM

- Active power sharing

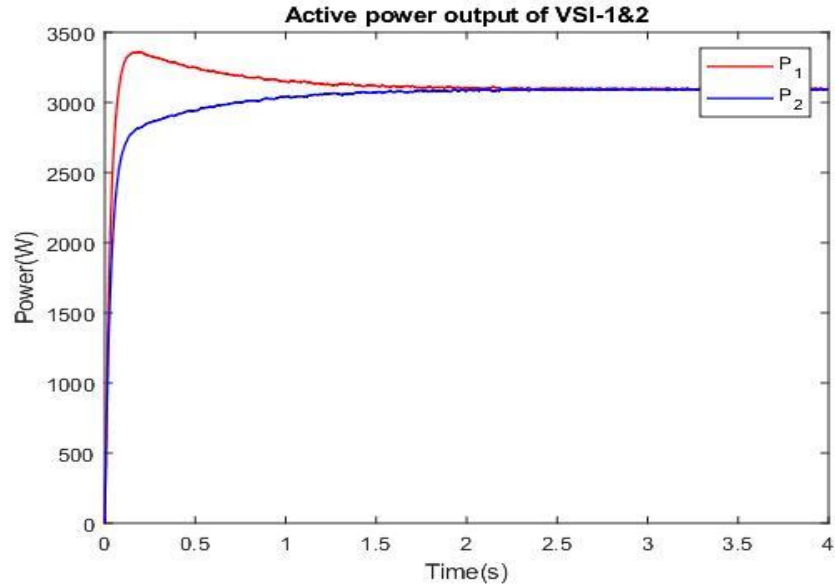


Fig.8.16 Sharing of active power in conventional system (Case-2)

2) BASE MODEL

- Active power sharing

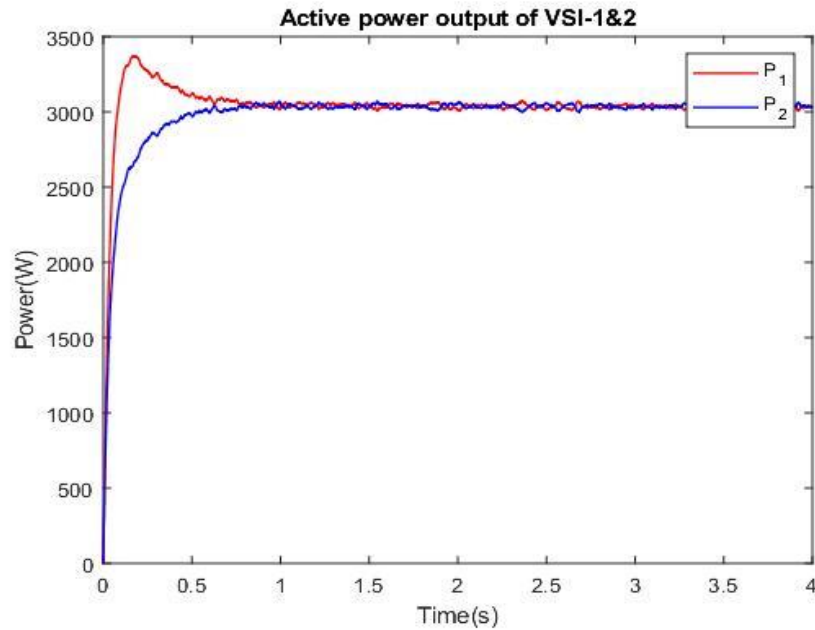


Fig.8.17 Sharing of active power in base model (Case-2)

3) MODIFIED SYSTEM

- Active power sharing

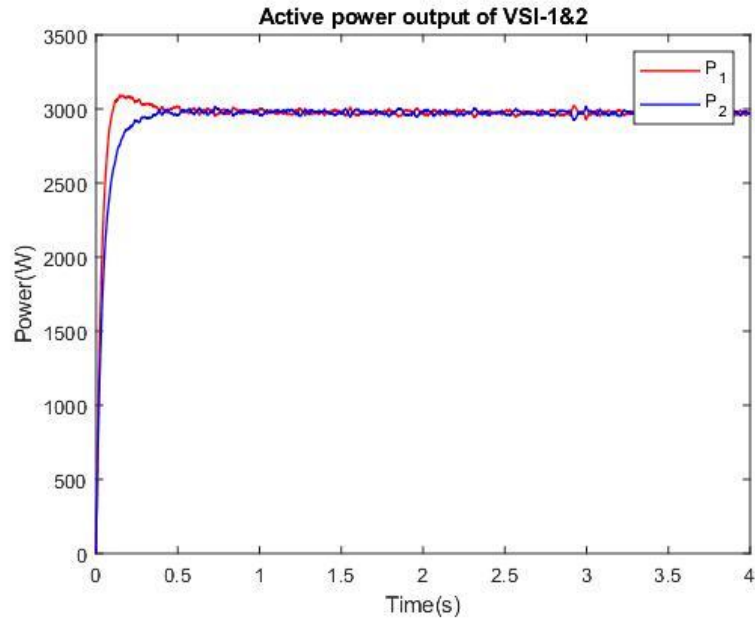


Fig.8.18 Sharing of active power in modified system (Case-2)

4) COMPARATIVE STUDY OF REACTIVE POWER UNDER THREE SYSTEMS

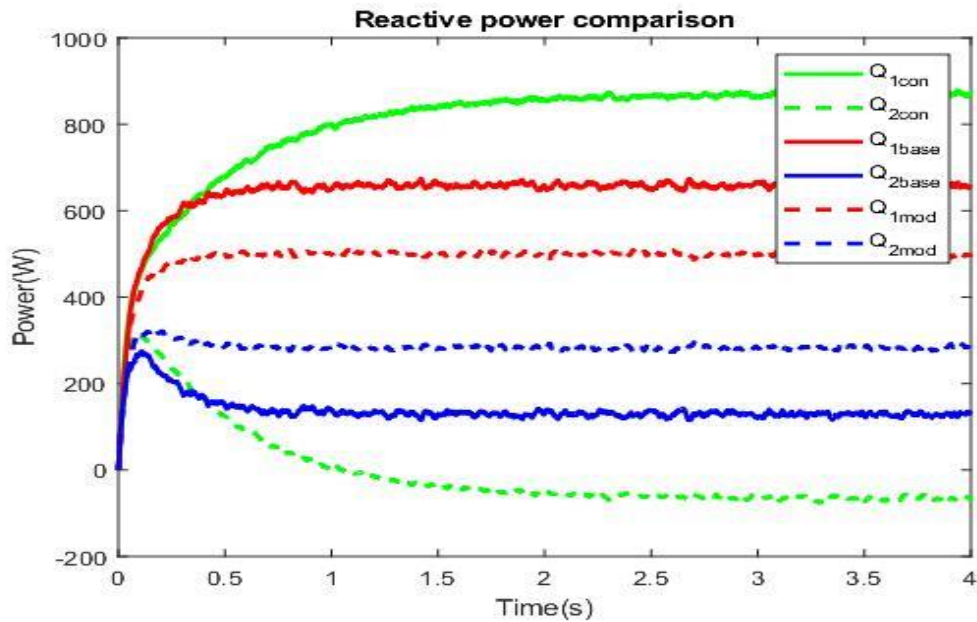


Fig.8.19 Sharing of reactive power - Comparison (Case-2)

- Q_{1con} and Q_{2con} are the reactive powers of the conventional system.
- Q_{1base} and Q_{2base} are the reactive powers of the base model.
- Q_{1mod} and Q_{2mod} are the reactive powers of the modified system.

From the comparative study done on MATLAB SIMULINK under unequal feeder impedance it is obtained that the real power is shared equally in conventional system, base model and modified system. The reactive power sharing is not equal in the three systems mentioned. The error in reactive power sharing is less in the modified system compared to the conventional system and base model. That is $\Delta Q_{mod} < \Delta Q_{base} < \Delta Q_{con}$.

❖ CASE-3: WITH UNEQUAL FEEDER IMPEDANCE AND LOCAL LOAD

Here an unequal feeder impedance of 1Ω , $1mH$ for feeder of VSI-1 and 1.25Ω , $1.25mH$ for feeder of VSI-2 is given and a load of 100Ω , $40mH$ is locally placed near VSI-1. Then this condition is checked for active power sharing and result is plotted for conventional system Fig.8.20, base model Fig.8.21 and modified system Fig.8.22. The comparative plot for reactive power sharing is shown in Fig.8.23.

1) CONVENTIONAL SYSTEM

- Active power sharing

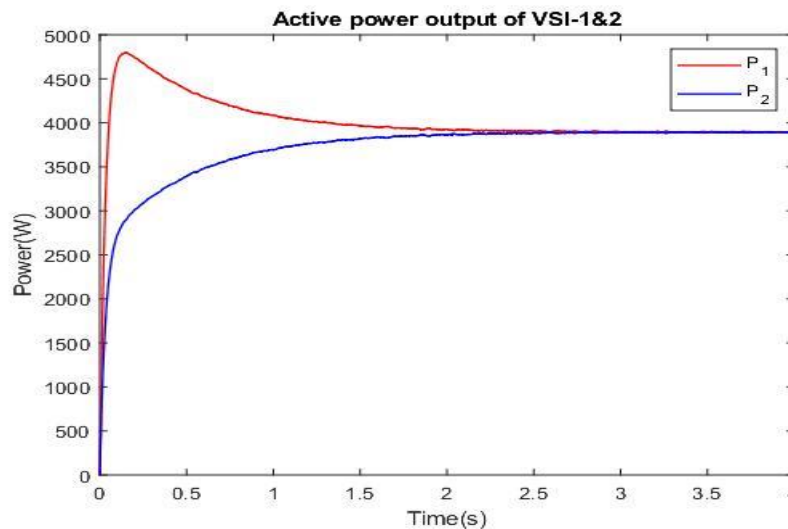


Fig.8.20 Sharing of active power in conventional system (Case-3)

2) BASE MODEL

- Active power sharing

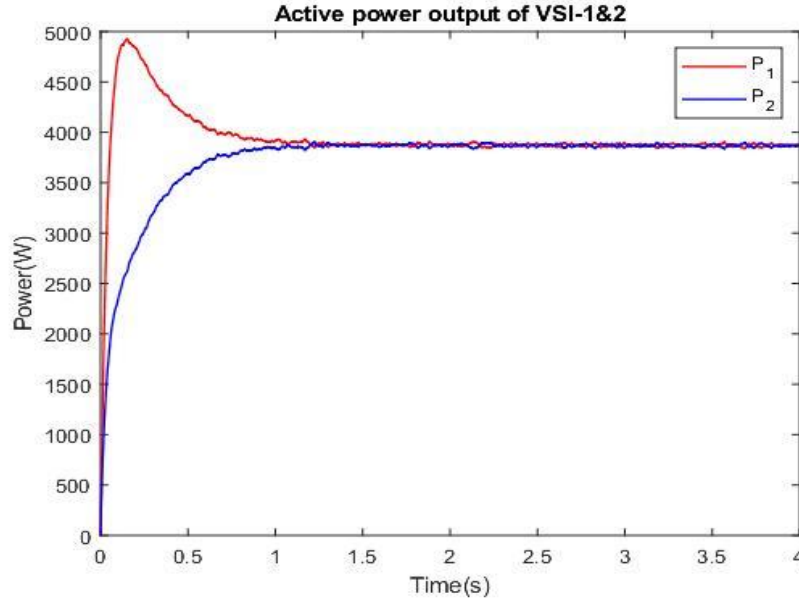


Fig.8.21 Sharing of active power in base model (Case-3)

3) MODIFIED SYSTEM

- Active power sharing

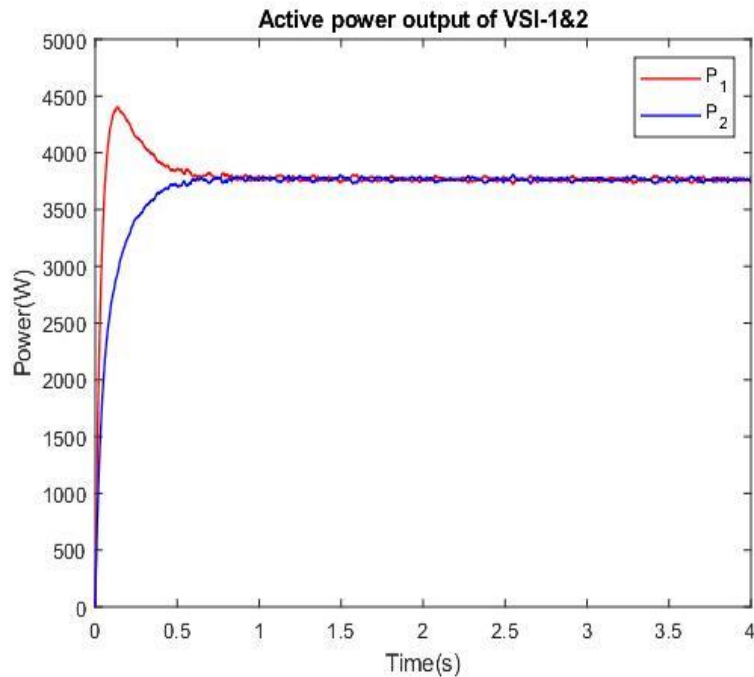


Fig.8.22 Sharing of active power in modified system (Case-3)

4) COMPARATIVE STUDY OF REACTIVE POWER UNDER THREE SYSTEMS

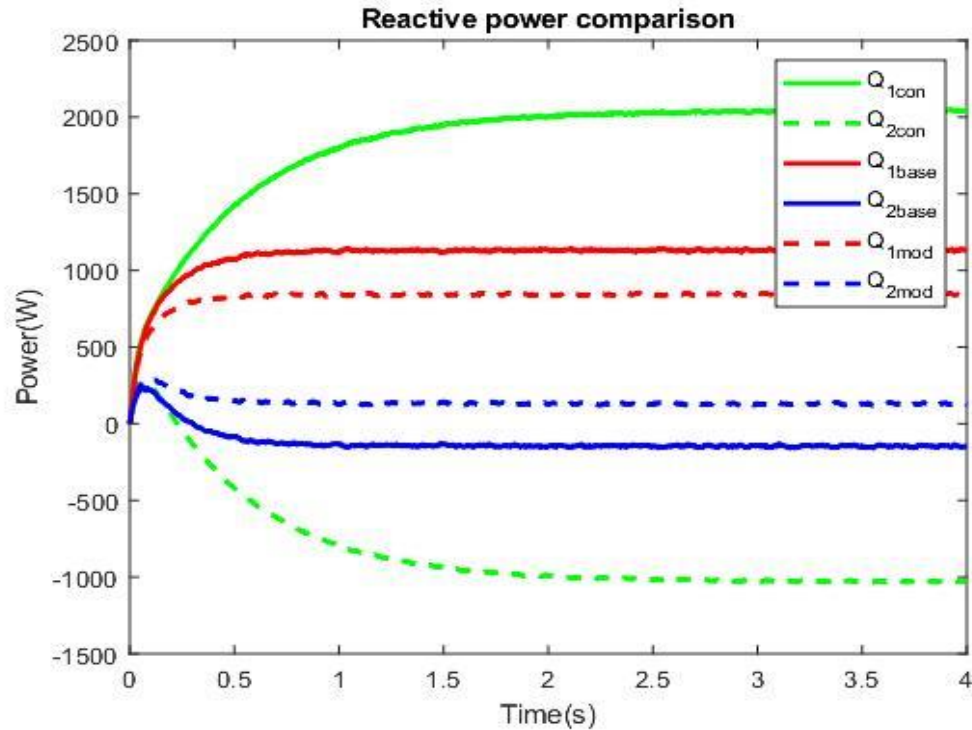


Fig.8.23 Sharing of reactive power - Comparison (Case-3)

- Q_{1con} and Q_{2con} are the reactive powers of the conventional system.
- Q_{1base} and Q_{2base} are the reactive powers of the base model.
- Q_{1mod} and Q_{2mod} are the reactive powers of the modified system.

From the comparative study done on MATLAB SIMULINK under unequal feeder impedance and local local load it is obtained that the real power is shared equally in conventional system, base model and modified system. The reactive power sharing is not equal in the three systems mentioned. The error in reactive power sharing is less in the modified system compared to the conventional system and base model. That is $\Delta Q_{mod} < \Delta Q_{base} < \Delta Q_{con}$.

8.3 Effect of droop slope in reactive power sharing

The effect of improved droop slope in reactive power sharing is discussed in chapter 5. In order to understand the effect of droop slope in reactive power sharing an improved droop slope is introduced in the base model under the condition having both parameters that is unequal feeder impedance and local load which affects the reactive power sharing.

- PCC voltage

The output voltage is maintained stable

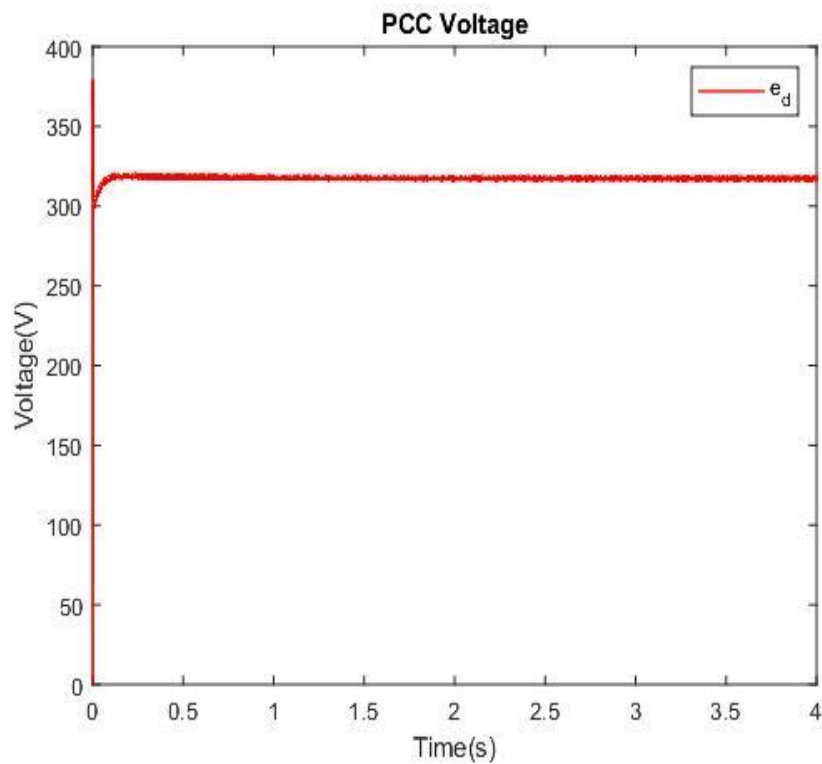


Fig.8.24 Voltage at point of common coupling in base model with improved droop slope

- Reactive power

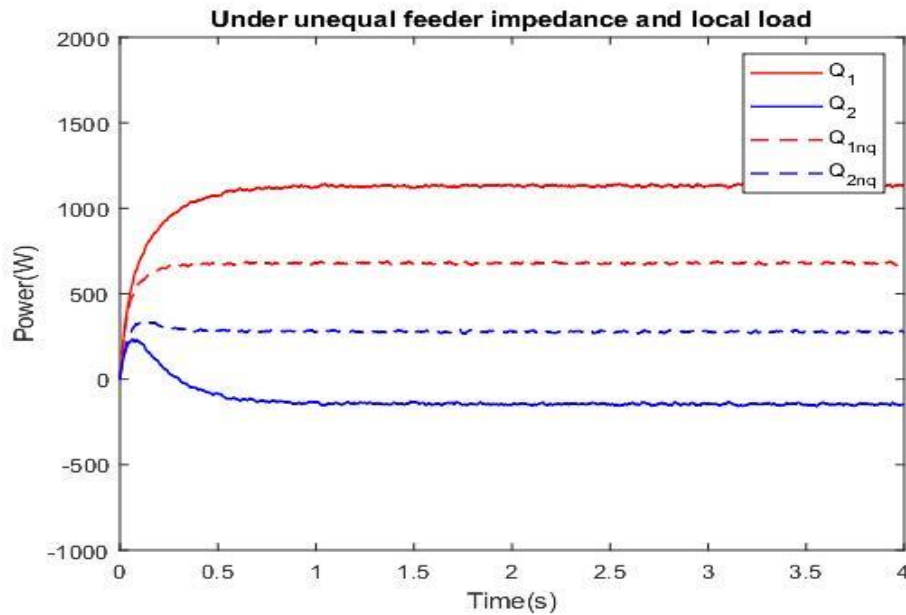


Fig.8.25 Reactive power sharing base model v/s base model with improved droop slope (Case-3)

- Q_1 and Q_2 are the reactive powers of the base model.
- Q_{1nq} and Q_{2nq} are the reactive powers of the base model with improved droop slope.
- From the Fig.8.25 it is evident that by improving the droop slope the error in reactive power sharing can be minimized.

CHAPTER 9

CONCLUSION

Reactive power is as an essential parameter in power system eventhough it is a wattless power. It helps in transforming the electron flow into useful work so that the active power could be delivered from source to load. The equal sharing of reactive power is vital. In power system if the reactive power is not shared equally it leads to overloading of distributed generators, cascaded tripping and increase circulating current. From the simulation model based on self-adjusting droop based strategy implemented on MATLAB/SIMULINK an almost accurate reactive power sharing in modified system compared to the conventional system is achieved. The effect of improved droop slope in reactive power sharing is studied under the condition with both unequal feeder impedance and local load.

PUBLICATION

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