ACCURATE REACTIVE POWER SHARING IN AN ISLANDED MICROGRID USING ADAPTIVE VIRTUAL IMPEDANCES

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ABSTRACT

An improved microgrid reactive power sharing strategy was proposed with linear loads and nonlinear loads. With linear load, the method injects a real-reactive power transient coupling term to identify the errors of reactive power sharing and then compensates the errors using a slow integral term for the DG voltage magnitude control. In addition, the proposed method is not sensitive to microgrid configurations, which is especially suitable for a complex mesh or networked microgrid. This proposed control method with non linear loads, the reactive power sharing introduces power transient and unequal power sharing by all DG units. A control strategy to improve reactive power sharing in an is-landed microgrid has been proposed by using STATCOM and validated in this project. The strategy employs communication to exchange the information needed to tune adaptive virtual impedances in order to compensate for the mismatch in feeder impedances. The control strategy does not require knowledge of the feeder impedances, and is straightforward to implement in practice. It is also in-sensitive to time delays in the communication channels. It has been shown that the proposed technique is tolerant of disruptions in the communication links while still outperforming the conventional droop control method. The sensitivity of the tuned controller parameters to changes in the system operating point has also been investigated. It has been shown that the system operating point is mainly determined by the power factor, and the higher the load power factor, the less sensitive the parameters are to the operating point. The effectiveness of the proposed system is designed using MATLAB software.

Keyword : - *Distribution generation, reactive power, microgrid, inverter.*

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1. INTRODUCTION

Distributed generation (DG) has recently received a great deal of attention as a potential solution to meet the increased demand for electricity, to reduce stress on the existing transmission system, and to incorporate more renewable and alternative energy sources. Subsequently, the microgrid concept has emerged as a promising approach to coordinate different types of distributed energy resources effectively by using local power management systems. A microgrid also allows the DG units to work in an islanded configuration, and therefore improves the availability and quality of power supplied to customers. However, islanded microgrids exhibit challenging control problems, such as the difficulty of maintaining generation load power balance and reactive power sharing. When a microgrid is operating in the islanded mode each DG unit should be able to supply its share of the total load in proportion to its rating. To achieve this, frequency and voltage droop control techniques that mimic the behavior of synchronous machines in conventional power systems are widely adopted in the literature. The reason for the popularity of the droop control technique is that it provides a decentralized control capability that does not depend on external communication links in the control strategy this enables “plug-and-play” interfacing and enhances the reliability of the system. Communication can, however, be used in addition to the droop control method to enhance the system performance without reducing reliability. Although the frequency droop technique can achieve accurate real power sharing, the voltage droop technique typically results in poor reactive power sharing due to the mismatch in the impedances of the DG unit feeders and also, due to the different ratings of the DG units. Consequently, the problem of reactive power sharing in islanded microgrids has received considerable attention in the literature and many control techniques have been developed to address this issue.

A comprehensive treatment of the virtual impedance concept to mitigate errors in reactive power sharing is presented. The focus has been on the mismatch in the output impedances of the closed loop controlled inverters that are used to interface the DG units. With proper design of the voltage controller, the closed loop output impedances must be negligible at steady state around the nominal operating frequency. Therefore, the virtual impedance is dominant, which results in accurate reactive power sharing. However, the analysis in did not consider the mismatch in the physical impedance of the feeders, including transformers, cables, and the interface inductors associated with each unit. A unique approach is proposed in to achieve accurate reactive power sharing. The proposed strategy requires injection of a small ac voltage signal in the system. Overlaying such an ac voltage signal may reduce the quality of the output voltage and line current. Also, extracting and processing this signal may result in a complicated implementation, particularly in a noisy environment. A control strategy employing inductive virtual impedance is developed in to ensure accurate reactive power sharing. The proposed analysis and design is based on the assumption that the feeder impedance is small and dominated by the virtual impedance, which is a known parameter. Moreover, the feeder physical impedance is estimated to improve the accuracy, and to include the effect of the impedance resistive component. The estimation technique requires the system to operate in grid connected mode first, before islanding. The technique is validated for a system with different virtual impedances, but with identical feeder physical impedances. On the other hand, the analysis and the control strategy introduced in requires that the feeder impedances are resistive. The analysis and the control strategy results in accurate power sharing if this condition is satisfied. In practice, however, the feeders may have both non-negligible inductive and resistive components.

Control strategies are proposed in and to achieve accurate power sharing among the inverters in an islanded microgrid. When the inverters are in close proximity an instantaneous control interconnection becomes feasible and can be used as an essential component to achieve accurate sharing. In Practice the DG units might be located in different geographic locations making this approach ineffective. An interesting control strategy is proposed in that the control strategy is composed of two stages: An initial conventional droop based control stage and A synchronized compensation stage.

During the synchronized compensation stage, the frequency droop is used to control the reactive power sharing. Since this action will also disturb the real power sharing, an integral control term is added to the voltage droop to maintain real power sharing accuracy. However, load changes during the compensation period or between compensation periods may result in poor power sharing. Communication is used to facilitate the estimation of the feeder impedances which are then used to set the virtual impedances to ensure accurate reactive power sharing. The feeder impedance is estimated at the local DG controller by utilizing the point of common coupling (PCC) voltage harmonic data transferred via a communication link. This is based on the assumption that the phase angle difference between the voltages at the PCC and at the inverter output is negligible. This assumption may not hold for long feeders or for higher power levels. The same technique is used under the same assumption.

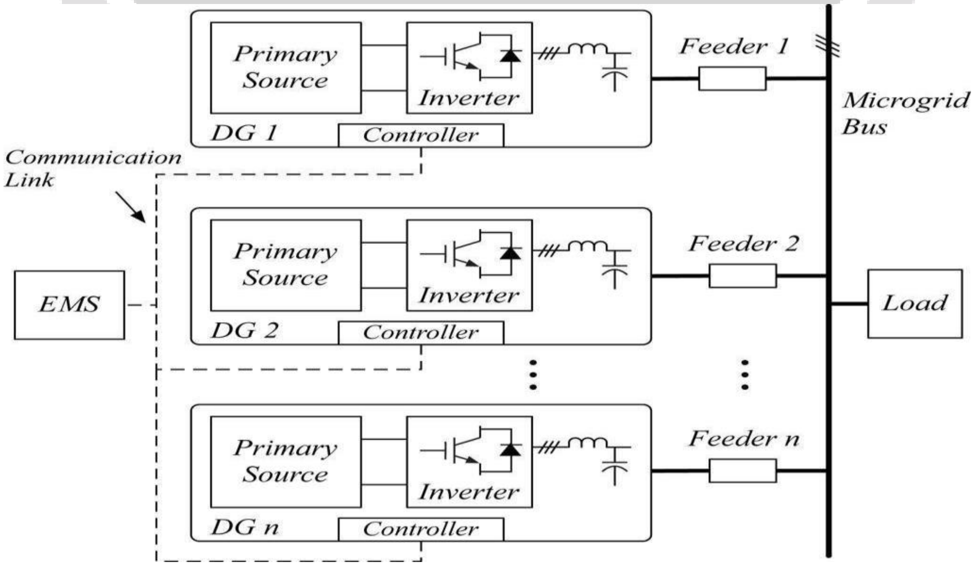


Fig-1: Islanded microgrid with communication links to an energy management system

Communication links are also used in to enhance the performance of conventional droop control. The proposed technique can reduce the sharing error but cannot eliminate it completely. For example, it reduces the maximum sharing error from 5.02 % to 3.05 %. Also, the performance of the technique is sensitive to delays in communication; e.g., a delay of 16 ms degrades the sharing accuracy significantly. A new droop control is proposed in to reduce the power sharing error. As in, the sharing error can be reduced but not completely eliminated and the improvement in performance is not significant if local loads are connected at the output of each unit. A distributed secondary control technique is proposed in to restore the frequency and the voltage, and also to ensure accurate reactive power sharing. In this technique, the controller is implemented in each DG unit instead of implementing it in the microgrid central energy management unit. Communication data drop-outs and packet losses are briefly discussed in the paper, however the scenario of a complete communication failure is not investigated.

In this paper, a control strategy that employs communication is proposed to enhance reactive power sharing accuracy. Communication is utilized to tune the adaptive virtual impedances in order to compensate for the mismatch in voltage drops across feeders. Once the virtual impedances are tuned for a given load operating point, the strategy will result in accurate reactive power sharing even if the communication is disrupted.

2. ISLANDED MICROGRID STRUCTURE AND CONTROL

2.1. Island microgrid structure

The structure of an islanded microgrid is shown in Fig. 1. The microgrid considered in this paper operates at the low-voltage power distribution level ($208Vl-l$). Each DG unit is connected to the microgrid bus through a feeder. The loads connected to the microgrid bus are lumped into a single load. The focus in this paper is on the fundamental real and reactive power sharing, and therefore only linear loads are considered. Each DG unit consists of a primary energy source, a three-phase inverter, and an LC filter. The feeder impedance includes the impedances of the interface inductor, isolation transformer, and the impedance of the feeder cables.

The local controllers can communicate information, such as real power and reactive power measured at the DG unit output, to the central energy management system (EMS) over a communication link. Since the proposed strategy only requires that the local controllers exchange data periodically at a slow rate, low-bandwidth communication links are considered adequate for this application. The local controller consists of the power controller, which generates the output voltage reference, and the voltage controller to track the voltage reference. Conventional frequency and voltage droop control is implemented in the controller.

$$\boldsymbol{\omega} \quad = \boldsymbol{\omega} - mPm \text{ ---------------} \qquad (1)$$

$$V^* \quad = Vo - nQm \text{---------------} \qquad (2)$$

P_m and Q_m are the real and reactive powers measured at the output of the DG unit, respectively, and are filtered to extract the fundamental power components. m is the frequency droop coefficient and n is the voltage droop coefficient. It is worth mentioning that to facilitate the utilization of the droop control concept in low-voltage distribution networks, a physical and/or a virtual interface inductor is commonly added in line at the output of the DG unit in an attempt to reduce the coupling between the real and the reactive power flows.

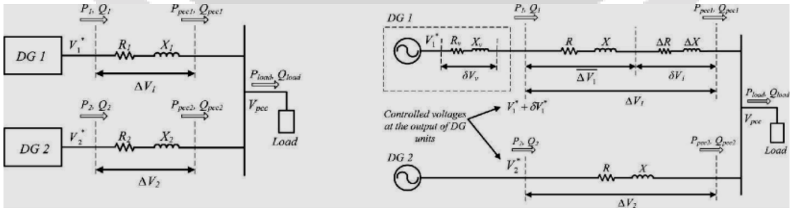


Fig-2: Simplified model of the microgrid with two Inverters and Detailed network model as seen from DG1

2.2. Reactive power sharing analysis

The effect of the feeder impedance mismatch on the reactive power sharing is examined by analyzing the voltage drop across the feeders. The voltage drop across the feeder impedance can be approximated as

$$V \quad = XQ+RP/\ V_O \text{ ----------------} \qquad (3)$$

where *X* and *R* represent the feeder reactance and resistance, *P* and *Q* represent the real and reactive power flowing through the feeder, respectively, and V_O is the DG unit nominal output voltage. Without loss of generality, a two unit microgrid as shown in Fig. 4 is used as a case study in this section. The voltage drops across Feeder 1 and Feeder 2 in Fig5 can be approximated by

$V1 = X1Q1+R1P1/Vo$ ------------------- (4)

$V2 = X2Q2+R2P2/Vo$ --------------------- (5)

The mismatch in the feeder impedance is given by

$X = X1-X2$ ------------------------- (6)

$R = R1-R2$ ------------------------- (7)

Xv and Rv stand for the effect of any virtual impedance that might be implemented in the controller. Note that with proper design of the conventional droop control, the voltages controlled and measured at the output filter capacitors of the DG units are assumed to match the references V1*+V1 and V2* at the steady state. P1, Q1, and P2, Q2 are the powers that can be measured at the outputs of the DG units.

$V1 = [(X+X)/Q1+(R+R)P1]/Vo$ ------------------- (8)

One solution to this problem is to mismatch the feeder impedances by using a virtual impedance of Xv = - X and Rv = - R

2.3. Proposed control strategy

The integral control is chosen such that the integration time is much longer than the information update period, e.g., the integration time $T_I = 1/K_I$ is chosen to be 200s·var/Ω, versus an information update period of 0.2 s. Therefore, the time delay in the received $Q*$ sample, due to the fact that reference $Q*$ is updated periodically, will have no effect on the reactive power sharing at steady state. This time delay is called the information update delay. Moreover, the tuning loop is slow enough that the interaction is negligible with the microgrid dynamics, which are dominated by the power low-pass filter dynamics. Note that the reference $Q*$ is calculated by the EMS based on the total reactive power load in the microgrid, therefore $Q*$ stays unchanged during the tuning action unless the total load changes. This part of the strategy can be considered to be a supervisory control system, which reacts only when the total load in the microgrid changes (a disturbance).

2.4. Tuned Controller Sensitivity to Operating Points:

The proposed controller is designed so that the tuned virtual impedance is held at its most recent value after a communication failure occurs, as will be illustrated in the following section. If the operating point remains unchanged after the communication failure, the sharing error will remain zero since the controller is already tuned for that operating point.

However, an operating point change will result in a sharing error because K_V can no longer adapt to the new operating point. The change needed in K_V to adapt to the new operating point defines the sensitivity of K_V with respect to the change in the operating point. To gain insight into the K_V sensitivity, the approximated relation.

$Kv = -[X+ R(P/Q)]/1+(P/Q)$ -------------------- (9)

From equation 9 that Kv depends on the ratio P/Q rather than on the value of P or Q separately.

2.5 Information Management Structure

The EMS periodically polls the inverters for their internally measured reactive power output. The update rate for the reactive power data can be chosen based on the specification of the available communication link. The collected reactive power measurements are then summed and weighted such that each inverter is responsible for sharing the reactive power in proportion to its rating. The resulting values are then passed back to the inverters as set points for the tuning control loop. The receiver is capable of detecting a communication time out, in which case the control loop is disabled and the integrator output will remain constant until a valid set point is again received. The timeout/enable logic in that when the EMS detects a communication timeout from one DG unit it blocks further set point updates to all the DG units until communication is restored. Since the updates are not sent to the remaining DG units their timeout/enable logic disables the tuning control loops until communication is restored. A binary EN is also sent along with the set point to allow for remote enabling and disabling of the tuning control loop.

3. ADAPTIVE VIRTUAL IMPEDANCE

To achieve accurate reactive power sharing regardless of the effects of mismatched line impedance, this paper proposes a reactive power sharing method that employs both consensus control and adaptive virtual impedance control for islanded microgrids. The consensus control is used to find the reactive power mismatch among distributed generation (DG) units. The reactive power mismatch term is fed to a proportional integral controller to generate the virtual impedance correction. With fully distributed regulation of the DG virtual impedance, the load reactive power will be shared accurately among DGs and the circulating line currents among DGs are effectively suppressed. The control strategy does not require the knowledge of the line impedances. Also, the average voltage restoration based on a dynamic consensus control is proposed to recover the decreased output voltage of each DG due to the droop action and the added virtual impedance. Simulation results show the effectiveness of the proposed method in achieving load reactive power sharing and the voltage restoration.

3.1. Introduction for Adaptive virtual impedances

With the growing concerns about the renewable energy, more renewable energy sources have been integrated in microgrid. However, the high penetration and increasing capacities of the renewable energy sources exhibit many challenging problems, such as the power quality and the system stability due to the intermittency of the renewable energy sources and the fluctuating load profile. To cope with these problems, the microgrid concept has been developed to realize flexible coordinate control among DG units. Microgrid that improves the availability and the power quality supplied to customers could be operated in grid-connected mode and islanded mode. In the case of islanded mode, the load demand should be properly shared by DG units. To satisfy the power sharing requirement without critical communications, the droop control method which mimics the behavior of a synchronous generator in microgrids has been widely adopted the droop control method that does not rely on external communication links enables **“**plug-and-play**”** of DG units. Recently, the hybrid microgrid architecture has been proposed to realize the load power sharing among different phases. However, in practical situations, although the frequency droop control can realize the accurate active power sharing, the voltage droop control typically results in poor reactive power sharing due to the mismatched line impedances and the difference of DG inverter parameters.

3.2. Energy management system

An energy management system (EMS) is a system of computer-aided tools used by operators of electric utility grids to monitor, control, and optimize the performance of the generation and/or transmission system. The computer technology is also referred to as SCADA/EMS or EMS/SCADA. In these respects, the terminology EMS then excludes the monitoring and control functions, but more specifically refers to the collective suite of power network applications and to the generation control and scheduling applications. Manufacturers of EMS also commonly supply a corresponding dispatcher training simulator (DTS). This related technology makes use of components of SCADA and EMS as a training tool for control centre operators. It is also possible to acquire an independent DTS from a non-EMS source such as EPRI. Energy management systems are also often commonly used by individual commercial entities to monitor, measure, and control their electrical building loads. Energy management systems can be used to centrally control devices like HVAC units and lighting systems across multiple locations, such as retail, grocery and restaurant sites. Energy management systems can also provide metering, sub metering, and monitoring functions that allow facility and building managers to gather data and insight that allows them to make more informed decisions about energy activities across their sites.

4. SIMULATION CIRCUIT AND RESULTS

4.1. BASIC MODEL

The performance of the system using only conventional droop control for two different loads. The total reactive power load is changed between 1030 and 388 var while the real power load is changed between 1215 and 910 W. These load settings represent a larger change in reactive power load as compared to the change in the real power load to show the low sensitivity of the tuned virtual impedance to the P /Q ratio factor (K_{PQ}) of the operating point. Also, this will help to evaluate the control strategy for a wide range of load power factors, from 0.76 for the higher load to 0.92 for the lower load. From figure the reactive power sharing accuracy under conventional droop control is as poor as 45 % for Unit 3 and 44% while it is 2.9 % for, calculated at the higher load operating point.

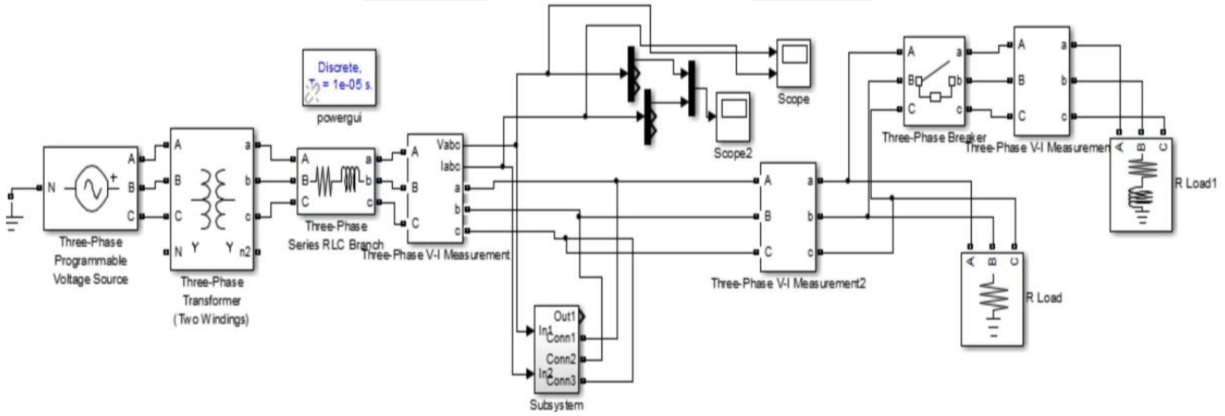


Fig-3: Basic model of microgrid

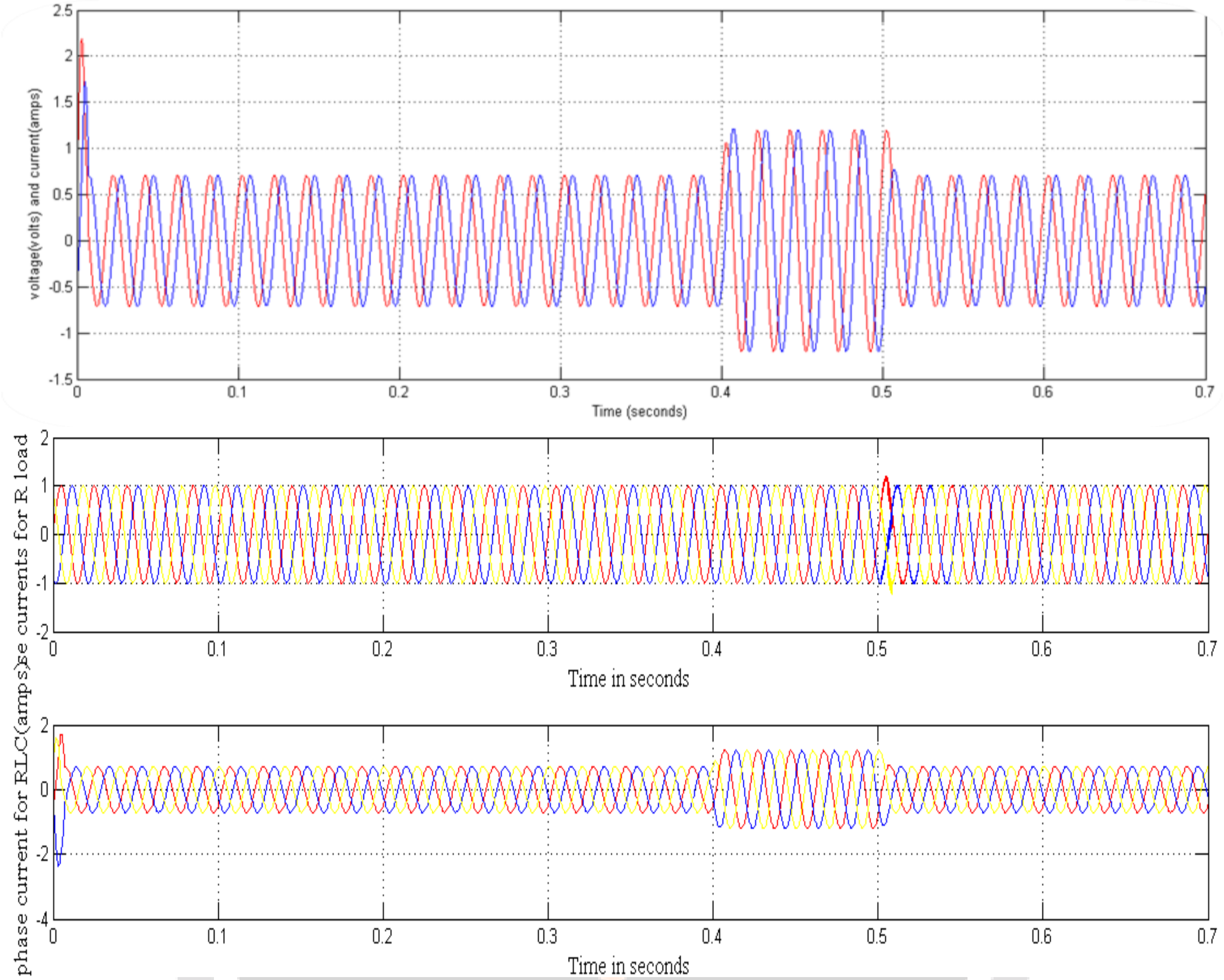


Fig-4: Power and current sharing under conventional droop control. Phase currents from each inverter for different load operating points

4.2 EXTENSION MODEL

The performance of the proposed controller the controller is enabled at t = 1 s which reduces the re-active power sharing error to zero in 2 s, the controller action has only a small transient effect on the real power supplied by each unit. The behavior of the microgrid bus voltage V_{pcc}, when the controller is enabled at T = 1 s, is shown in Fig. 10. As can be seen, the voltage drop introduced by the proposed controller is negligible (0.0015pu). This is due to the fact that controllers reduce the total feeder impedance for the unit with the higher physical impedance, and increase it for the unit with the lower physical impedance, as can be noticed. The latter voltage change, when the load stepped down, is mainly due to the change in the voltage drop across the feeders and the conventional voltage droop action, since the virtual impedances did not change significantly when the load changed.

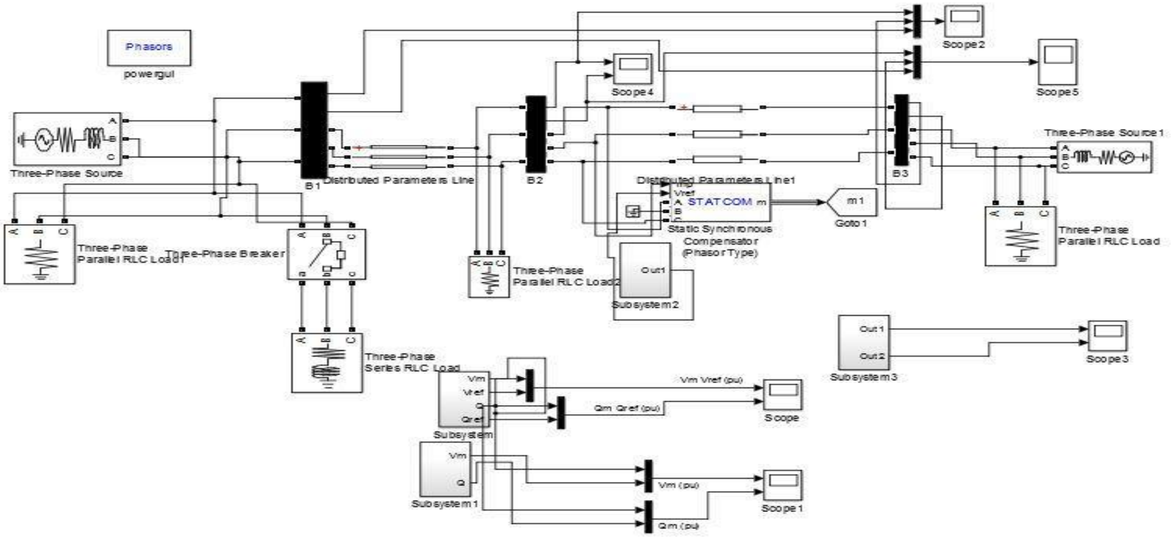
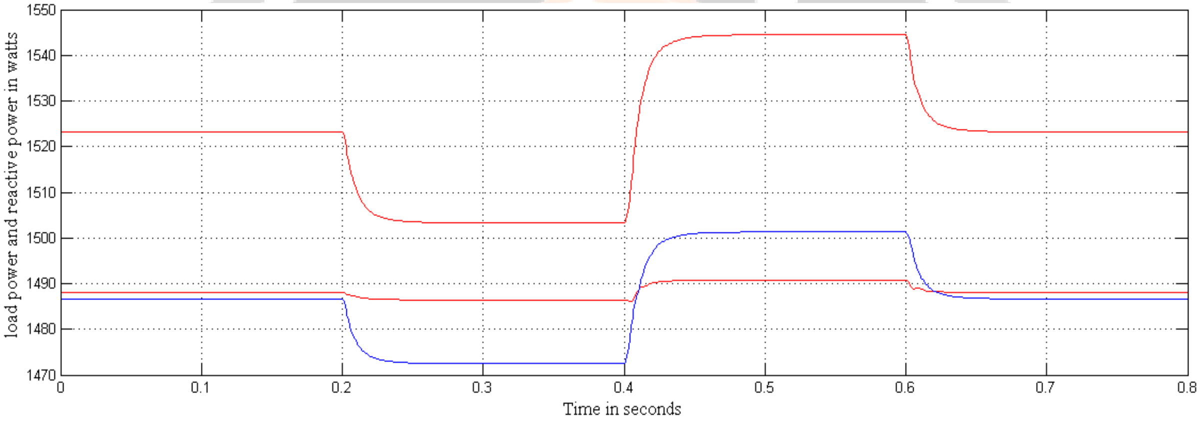
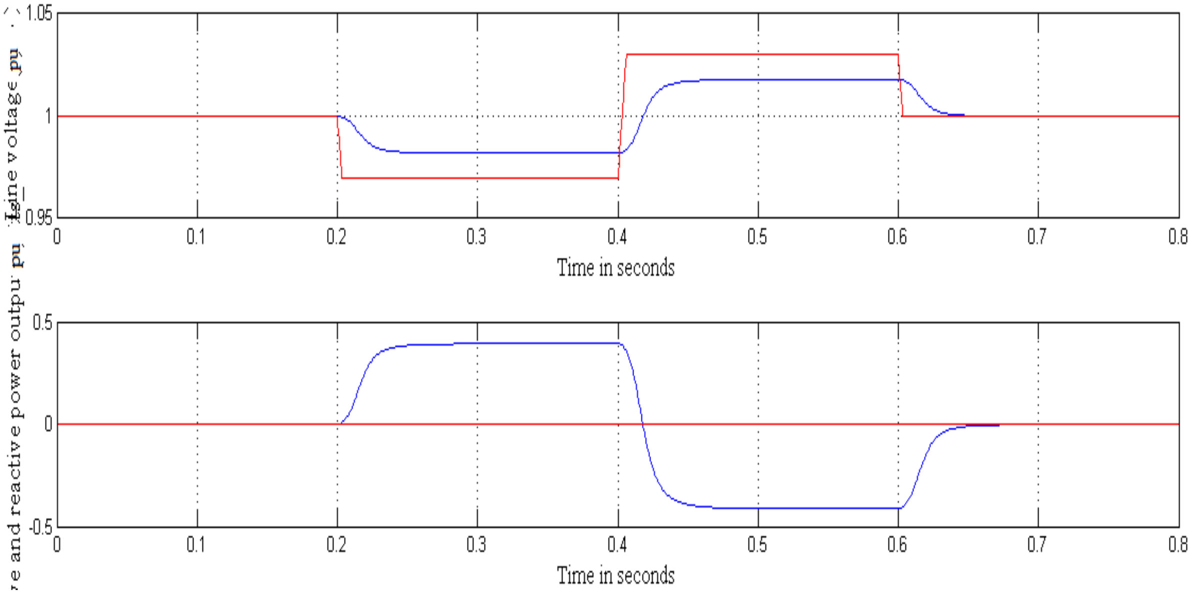


FIG-5: Extension model of a basic model





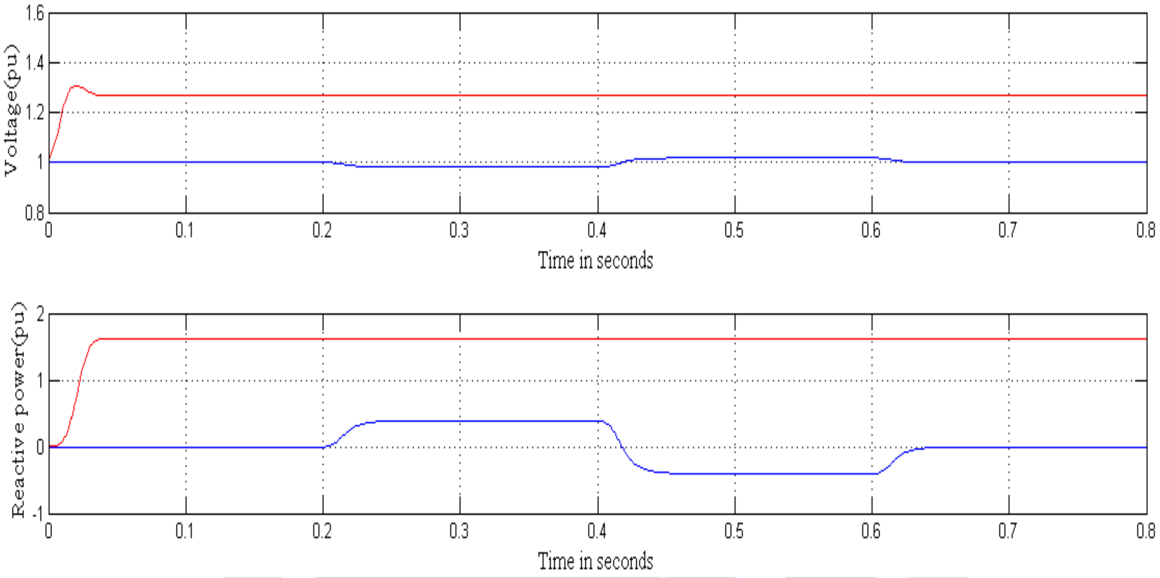


Fig-6: Real and Reactive power sharing. step change in the load operating point with the controller enabled. The steady state reactive power for each inverter steps from 665 to 445 var and back.

5. CONCLUSIONS

An improved microgrid reactive power sharing strategy was proposed with linear loads and nonlinear loads. With linear load, the method injects a real-reactive power transient coupling term to identify the errors of reactive power sharing and then compensates the errors using a slow integral term for the DG voltage magnitude control. In addition, the proposed method is not sensitive to microgrid configurations, which is especially suitable for a complex mesh or networked microgrid. This proposed control method with non linear loads, the reactive power sharing introduces power transient and unequal power sharing by all DG units. A control strategy to improve reactive power sharing in an is-landed microgrid has been proposed by using STATCOM and validated in this project. The strategy employs communication to exchange the information needed to tune adaptive virtual impedances in order to compensate for the mismatch in feeder impedances. The control strategy does not require knowledge of the feeder impedances, and is straightforward to implement in practice. It is also in-sensitive to time delays in the communication channels. It has been shown that the proposed technique is tolerant of disruptions in the communication links while still outperforming the conventional droop control method. The sensitivity of the tuned controller parameters to changes in the system operating point has also been investigated. It has been shown that the system operating point is mainly determined by the power factor, and the higher the load power factor, the less sensitive the parameters are to the operating point. The control strategy has been simulated and implemented in a 2-kVA experimental system and has been verified to be effective under operating point changes and realistic communication failures.

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