



Research paper

Distributed secondary controller to ensure proportional sharing of reactive power in AC microgrid

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ABSTRACT

In an ac microgrid, reactive power sharing accuracy is affected due to unequal values of interconnecting cable impedances. To resolve this issue, secondary controllers are used to compensate the effect of cable impedances. Various types of secondary controllers are suggested in the literature which includes linear proportional plus integral (PI) controllers to minimize the difference in reactive power sharing created by conventional $E - Q$ droop law. The reference value of the PI controller is the average value of reactive powers supplied by the sources. When the PI controller is used to minimize the difference between the actual and reference value of reactive power, the difference between the algebraic sum of reactive powers supplied by the sources and the reactive powers demanded by the loads has a nonzero value. Therefore, the performance of these controllers becomes poor in the case of ac microgrid having sources of unequal ratings. To resolve this issue, a proportional reactive power-sharing (PRPS) controller-based distributed secondary controller is proposed in this paper. The PRPS controller modifies the droop gain of the $E - Q$ droop control loop of each source in such a way that each source supplies reactive power equal to its proportional value of reactive power. The proportional value of reactive power supplied by each source is the power when the equivalent output impedance of all sources as seen by the loads are identical. The key advantage offered by the proposed controller is the accurate reactive power-sharing in the case of ac microgrid having sources of unequal ratings. The proposed controller ensures zero value of the difference between the algebraic sum of reactive powers supplied by the sources and the reactive powers demanded by the loads. This ensures accurate sharing of reactive power among the sources. The validation of the proposed controller is carried out for islanded mode of operation of ac microgrid. Further, the proposed controller requires of low bandwidth communication for its implementation. The effect of the proposed controller on the stability of the system is demonstrated using reduced order small-signal model. The effect of communication delay on the performance of the system is analyzed with the help of roots locus plots. To validate the efficacy of the proposed controller, detailed simulation studies are carried out in Matlab/Simulink.

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1. Introduction

In ac microgrid, conventional $\omega - P$ and $E - Q$ droop control laws are widely used to ensure proportional sharing of active and reactive powers demanded by loads among the sources in the islanded mode of operation (Guerrero et al., 2004; Loh et al., 2014). However, frequency is a universal parameter. Therefore, the active power-sharing at a steady state is accurate. However, the performance of $E - Q$ droop control law deteriorates due to unequal values of feeder or interconnecting cable impedances (He

and Li, 2012). If the feeder impedances are highly mismatched, it may result in flow of circulating reactive power of large magnitude and operation of microgrid may become unstable (Guerrero et al., 2005; Han et al., 2015; Issa et al., 2019). The unequal nominal voltages of sources due to the error in sensors may also lead to the flow of circulating reactive power (Simpson-Porco et al., 2017). Reactive power-sharing accuracy is further deteriorated due to unequal local loads connected at the output of sources (He and Li, 2012; Cheng et al., 2009). The reactive power sharing inaccuracy may lead to overloading of sources and may hamper their power handling capacity (Li and Kao, 2009). Therefore, for the stable and efficient operation of ac microgrid, it is necessary to ensure the proportional sharing of reactive power.

To compensate the mismatching in feeder impedances, virtual impedance techniques are suggested in literature (Yao et al.,

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2011; Mahmood et al., 2015a; Zhang et al., 2016). In Yao et al. (2011), the virtual impedance technique modifies the output impedance of each source in such a way that effective output impedances of all sources are equivalent. However, the suggested technique requires the manual adjustment of virtual impedance parameters until the value of circulating reactive power flowing among the sources is minimized. To avoid manual adjustment of parameters, the schemes reported in Mahmood et al. (2015a) uses communication between the sources for adaptive adjustment of the virtual impedance parameters. However, the problem of data congestion in Mahmood et al. (2015a) may deteriorate the performance of the suggested method. To reduce the impact of data congestion, consensus-based virtual impedance methods is suggested in Zhang et al. (2016). However, in consensus-based methods, the rate of convergence of these systems to the final steady-state value is slow during transient conditions as discussed in Olfati-Saber and Murray (2004). Further, poor design and inaccurate implementation of virtual impedance may affect the dynamics and stability of the system and may introduce distortions in active and reactive power (He and Li, 2011).

The droop controller may not able to minimize the difference in reactive powers supplied by sources. To resolve this issue, additional controllers are used along with droop controllers. To compensate the effect of interconnecting cable impedances, secondary controllers are suggested in literature to minimize the error in reactive power sharing in ac microgrid (Rey et al., 2020). Various types of secondary controllers are discussed in detail in Khayat et al. (2020), Han et al. (2017). The secondary controllers discussed in Guerrero et al. (2011), Micallef et al. (2014, 2015), Han et al. (2016) are centralized one. In Guerrero et al. (2011), the linear PI controller is used to minimize the error between the nominal value of reactive power and actual value of reactive to be supplied by each source. In Micallef et al. (2014), the microgrid central controller (MGCC) is used to improve reactive power sharing accuracy. The suggested controller includes a linear PI controller to minimize the error between the actual and proportional value of reactive power. The output of MGCC is added to the voltage droop controller. To ensure a seamless transition from grid-connected mode to islanded mode, an improved MGCC is suggested in Micallef et al. (2015). To improve the performance of ac microgrid against harmonic sharing and unbalance voltage compensation in ac microgrid, a modified MGCC is suggested in Han et al. (2016). The modified MGCC ensures proportional sharing of reactive power. However, the reliability of the centralized secondary controller suggested in Guerrero et al. (2011), Micallef et al. (2014, 2015), Han et al. (2016) is less and its scalability is low.

To enhance the modularity and reliability of ac microgrid, distributed secondary controllers are used (Han et al., 2015; Shafiee et al., 2014; Mahmood et al., 2015b). In Han et al. (2015), the suggested controller shifts $E - Q$ droop characteristics vertically to minimize the reactive power sharing error. However, the convergence of reactive power to its reference value requires the accurate measurement of voltage drops across the feeder impedances. In Shafiee et al. (2014), conventional PI controllers are used to shift the $f - P$ and $E - Q$ droop characteristics, to minimize the error in active and reactive power-sharing. The reference values of PI controller used in the distributed secondary controller is equal to the average value of reactive powers supplied by sources. Therefore, the reactive sharing accuracy of the controller may become poor in the case of ac microgrid having sources of unequal ratings. In Mahmood et al. (2015b), adaptive variation in slope of $E - Q$ droop characteristics is carried out. The output of PI controller adjusts the slope of $E - Q$ droop characteristics. The suggested method delivers a high degree of accuracy in reactive power-sharing. However, the centralized Energy Management

System (EMS) is required to evaluate the value of reference power to be shared by each source, which requires initial information of source capacity and load on ac microgrid. The implementation of the suggested technique may be difficult in the case of an ac microgrid with multiple sources and loads. To overcome this limitation, a centralized secondary controller along with modified droop and virtual impedance controllers are discussed in Lin et al. (2017). The modified droop controller along with the virtual impedance loop ensures stable operation of the ac microgrid. The secondary controller and virtual impedance loop collectively minimize the difference in active and reactive powers supplied by sources. However, inaccurate implementation and poor design of virtual impedance technique may lead to power quality and stability issues in ac microgrid. The reference value of the PI controller used in above mentioned secondary controllers is equal to the average value of reactive powers supplied by sources. The reactive power sharing accuracy of the controller becomes poor in the case of ac microgrid having sources of unequal ratings. Further, the communication burden in the case of the above-mentioned controllers may increase with increases in the number of sources in the system.

To reduce the effect of communication congestion, a low bandwidth sparse communication is used in Nasirian et al. (2016), Espina et al. (2021), Shi et al. (2020) to shift the droop characteristics. The $E - Q$ droop characteristics of sources are shifted parallel to voltage axis to ensure proportional sharing of active and reactive power and to maintain voltage regulation at each bus of ac microgrid within the specified limits. The cyber-physical network with reduced communication is used to implement a cooperative control framework within the system. Cooperative decision-making increases the scalability and reliability of the system against communication link failure. However, the system with reduced communication takes more time to reach a steady-state after a disturbance as compared to the system with all-to-all communication (Olfati-Saber and Murray, 2004).

To enhance the power quality, efficiency and reliability of ac microgrid, nonlinear secondary controllers are suggested in Heydari et al. (2019), Navas-Fonseca et al. (2021) and Biglarahmadi et al. (2021). The secondary controller based on finite control set model predictive control (FCS-MPC) is suggested in Heydari et al. (2019). The FCS-MPC controller enhances the stability margin of ac microgrid against the parameters variation and ensures proportional sharing of active and reactive powers. To enhance the flexibility of control in ac microgrid, a distributed MPC (DMPC) is suggested in Navas-Fonseca et al. (2021). To ensure very accurate reactive power sharing in ac microgrid, an exponential secondary controller is suggested in Biglarahmadi et al. (2021). The controllers suggested in Heydari et al. (2019), Navas-Fonseca et al. (2021) and Biglarahmadi et al. (2021) are nonlinear in nature. The practical implementation becomes difficult due to the nonlinear nature of these controllers.

The penetration of unbalanced and nonlinear loads in ac microgrid may lead to various power quality issues such as voltage imbalance and harmonics in line current (Gao et al., 2017; Savaghebi et al., 2013). However, the convention droop control laws which are $\omega - P$ and $E - Q$ are primarily used to ensure proportional sharing of the fundamental component of active and reactive power. These controllers are used to share the average value of active and reactive power and the harmonic current sharing is not affected (De and Ramanarayanan, 2010). The value of harmonic current to be supplied by the source inverter is dominantly affected by its output impedance or impedance of the line. Virtual impedance methods are dominantly used to reduce the impact of line impedance and to ensure accurate sharing of harmonic current (Lazzarin et al., 2013; Guan et al., 2016).

To ensure proportional sharing of unbalance power and harmonic currents in ac microgrid, the various techniques are suggested in literature which are broadly classified into two categories which are named as the techniques requiring communication and without communication. A Harmonic current feed-forward technique is proposed in Sree Kumar and Khadkikar (2017) in which harmonic components of inverter current are used to generate feedforward signals. These signals are used in the inner current control loop of the inverter to ensure harmonic current sharing. However, the performance of the proposed controller becomes poor in case of large mismatching among line parameters. To achieve good harmonic sharing accuracy and improved voltage profile, a virtual resistance–capacitance (R–C) impedance method is used in Micallef et al. (2017). To ensure proportional harmonic current sharing among inverters, the virtual resistance is emulated. The inductance of the transmission line is canceled out using the emulated virtual capacitance. Using this technique, the voltage profile of the source is improved. However, the performance of the suggested method deteriorates in the case low voltage microgrid due to the predominantly resistive nature of transmission lines. To resolve this issue, negative resistance emulation based method is suggested in Sree Kumar and Khadkikar (2016). Using the power capacity of the inverter, negative resistance is evaluated. However, it may lead to unstable operation of ac microgrid if negative emulated resistance is more than the line impedance. Communication-based techniques are suggested in Han et al. (2016), He et al. (2013). In Han et al. (2016), a centralized controller is suggested in which harmonic compensation references are generated in the central controller and finally communicated to the local controller. However, the suggested controller suffers from the limitation of a single point of failure. To overcome this problem, the distributed controller is suggested in He et al. (2013). In He et al. (2013), the adjustment for inverter output impedance is carried out by measuring the harmonic component of load side voltage. Using a communication channel, the load voltage is communicated to each, and a harmonic reference is generated. However, the technique suggested in He et al. (2013) requires the prior information of load line parameters.

In response to the above-mentioned issues, a distributed linear secondary controller is proposed in this paper which is named as Proportional Reactive Power Sharing (PRPS) controller. The proposed controller is able to ensure accurate sharing of reactive among the sources. For this purpose, the controller evaluates the proportional value of reactive power to be supplied by each source. The proportional value of reactive power supplied by each source is the power when the equivalent output impedance of all sources as seen by the loads are identical. Depending upon the difference between the proportional and the actual value of reactive power, the proposed controller modifies the droop gain of the $E - Q$ droop control loop of each source in such a way that each source supplies reactive power equal to its proportional value of reactive power. The performance of the linear PI controller-based secondary controllers discussed in the literature becomes poor in case ac microgrid has sources of unequal capacity. However, the proposed controller ensures a high degree of accuracy in reactive power-sharing. The validation of the proposed controller is carried out for islanded mode of operation of ac microgrid.

The salient features of the proposed controller are as follows:

1. A distributed secondary controller named as Proportional Reactive Power Sharing (PRPS) controller is proposed which renders an ac microgrid into an ac microgrid in which equivalent impedances of all sources are equivalent. Excellent reactive power sharing performance is achieved in ac microgrid.

2. Proportional value of reactive power to be supplied by each source is calculated by using summation of reactive powers supplied by each converter and initial values of droop gains of all sources. This information is supplied with the help of a low bandwidth communication channel.
3. The proposed controller ensures accurate sharing of reactive in case of ac microgrid having sources of unequal ratings.
4. The performance of the controller is validated with various linear loads like $R-L$, $R-C$ and Unity Power Factor Rectifier (UPFR).

Further, the effect of the proposed controller on the stability of the system is demonstrated using reduced order small-signal model. The effect of communication delay on the performance of the system is analyzed with the help of roots locus plots. To validate the efficacy of the proposed controller, detailed simulation studies are carried out in Matlab/Simulink.

2. Proposed distributed secondary controller

In this section, the PRPS controller used to ensure proportional sharing of reactive power is discussed. Fig. 1 shows the control scheme of three phase voltage source inverter (VSI) of j th source including the PRPS controller. The controller action requires the calculation of proportional reactive power to be supplied by this source. Using the proportional value of reactive power, the controller modifies the gain of $E - Q$ droop characteristics to converge the reactive power to its proportional value. The procedure for evaluation of the proportional value of reactive power to be supplied by the source is discussed in the next subsection.

2.1. Evaluation of proportional reactive power

The $E - Q$ droop law is used to share reactive power in ac microgrid. For j th source, it is expressed as

$$e_j = E_{oj} - k_{qj}q_{jj} \tag{1}$$

where, E_j is the reference voltage, E_{oj} is the nominal value of voltage, k_{qj} is the droop gain and q_{jj} is the reactive power supplied by j th source.

Corresponding to a given distribution of loads in ac microgrid, the reactive powers supplied by sources are $q_{f1}, q_{f2} \dots q_{fj} \dots q_{fn}$. Considering the case in which the equivalent output impedances of all sources are identical as seen from load side, the proportional values of reactive powers supplied by the sources for this case are, $q_{f1}^{pro}, q_{f2}^{pro} \dots q_{fn}^{pro}$ which are related by the following relation,

$$k_{q1}q_{f1}^{pro} = k_{q2}q_{f2}^{pro} \dots = k_{qn}q_{fn}^{pro} \tag{2}$$

Here, $k_{q1}, k_{q2} \dots k_{qn}$ are initial values of droop gains of sources. However at steady state, the sum of reactive powers supplied by the sources in actual and the case in which equivalent impedances of sources are identical will remain same. Therefore, the expression for total reactive power q_{js} is given by,

$$q_{js} = q_{f1} + q_{f2} \dots + q_{fn} = q_{f1}^{pro} + q_{f2}^{pro} \dots + q_{fn}^{pro} \tag{3}$$

Using (2) and (3), the proportional value of reactive power to be supplied by j th source is

$$q_{jj}^{pro} = \frac{\sum_{j=1}^n q_{fj}}{k_{qj} \sum_{j=1}^n \frac{1}{k_{qj}}} = \frac{k_{qs}q_{js}}{k_{qj}} \tag{4}$$

The proportional value of reactive to be supplied by each source to compensate the effect of unequal values of interconnecting cable impedances can be calculated using (4). The evaluated value of q_{jj}^{pro} is used to modify the instantaneous value of gain of $E - Q$

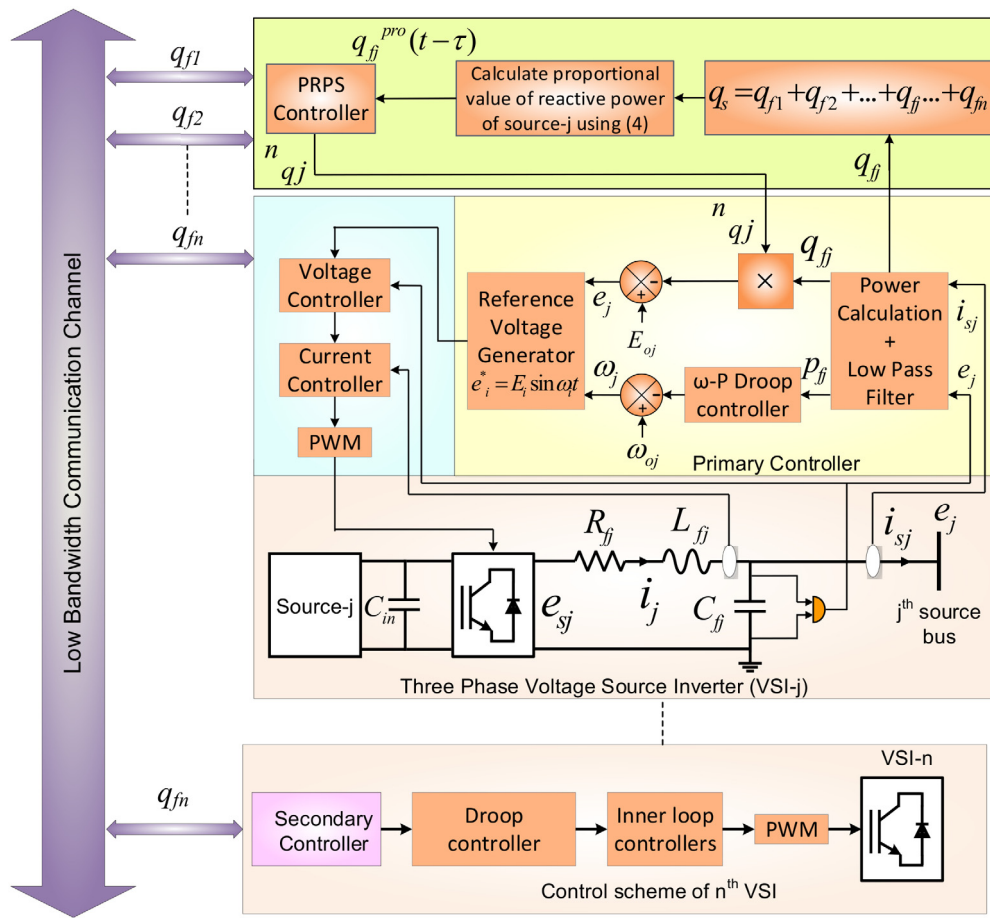


Fig. 1. Control scheme of three phase VSI with proposed PRPS controller.

droop controller of j th source. Considering that the instantaneous value of $E - Q$ droop gain of j th source represented as n_{qj} , the modified value of n_{qj} is given by

$$n_{qj}[u] = n_{qj}[u - 1] + h_j(q_{fj} - q_{fj}^{pro}) \tag{5}$$

Here, $n_{qj}[u]$ and $n_{qj}[u - 1]$ are the updated and previous sampled values of n_{qj} . The element, h_j is a constant and its value depends upon the rate of change of n_{qj} . A tolerance band represented by ε is set between q_{fj} and q_{fj}^{pro} within the controller. Depending upon value of ε , the output of secondary controller of j th source is given by,

$$n_{qj}[u] = \begin{cases} n_{qj}[u - 1] + h_j(q_{fj} - q_{fj}^{pro}) & \text{for } (q_{fj}^{pro} - q_{fj}) > \varepsilon; \\ n_{qj}[u - 1] & \text{for } (q_{fj}^{pro} - q_{fj}) < \varepsilon; \end{cases} \tag{6}$$

The control law given by (6) is valid only for $R-L$ loads. However, in case of $R-C$ and active loads like three phase UPFR, the value of $q_{fj} < 0$ and $q_{fj} = 0$. For these types of loads, the variation in n_{qj} given by (6) will no longer be able to converge q_{qj} to q_{qj}^{pro} . To overcome this issue, the modified output of secondary controller is

$$n_{qj}[u] = \begin{cases} n_{qj}[u - 1] + h_j(|q_{fj}| - |q_{fj}^{pro}|) & \text{for } |q_{fj}^{pro} - q_{fj}| > \varepsilon; \\ n_{qj}[u - 1] & \text{for } |q_{fj}^{pro} - q_{fj}| < \varepsilon; \end{cases} \tag{7}$$

The control scheme of VSI with detailed diagram of PRPS controller is shown in Fig. 2. The digital controller executes the Eq. (6) after every time period of T_s . During steady state, the difference between q_{fj} and q_{fj}^{pro} is less than ε , the controller takes not action. However, during step variation in load demand,

controller modifies the value of n_{qj} to converge the value of q_{fj} near to q_{fj}^{pro} . As soon as the value of $(q_{qj}^{pro} - q_{fj})$ becomes less than ε , the controller action stops modifying the instantaneous value of droop gain, n_{qj} .

Fig. 3 shows the effect of PRPS controller on the $E - Q$ droop characteristics of source- j connected in ac microgrid. The PRPS controller modifies the slope of $E - Q$ droop characteristics to converge q_{fj} near to q_{fj}^{pro} . The output of proposed secondary controller given by (7) ensures accurate reactive power sharing for the loads like $R-L$, $R-C$ and UPFR load as shown in Figs. 3(a), 3(b) and 3(c). The flow chart for the PRPS controllers is shown in Fig. 4.

2.2. Effect of line parameters on reactive power sharing

In ac microgrid, the droop controller modifies the operating voltage frequency and voltage magnitude by emulating droop characteristics of synchronous generator. By modifying the frequency of voltage and magnitude of voltage, the active and reactive power to be dispatched by the source can be regulated in such a way that each source supplies power in proportion to its rated capacity. To control the dispatch of active and reactive power using the droop control laws, the relations of active and reactive powers supplied by two sources with frequency of voltage and magnitude of voltage are to be taken into consideration (De Brabandere et al., 2007).

Expressions for active and reactive power flow between two sources: Fig. 5 shows the source- i and source- j interconnected by the cable having impedance, $Z_{ij} = R_{ij} + jX_{ij}$. The expression for the

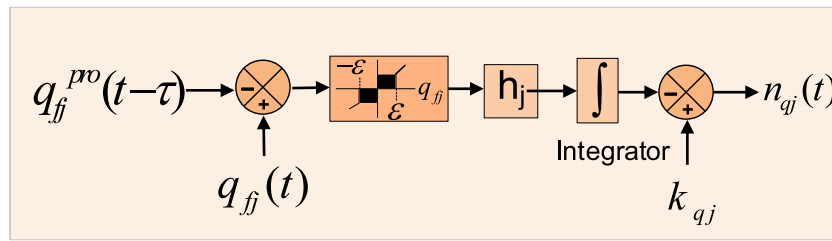


Fig. 2. Time domain model of PRPS controller.

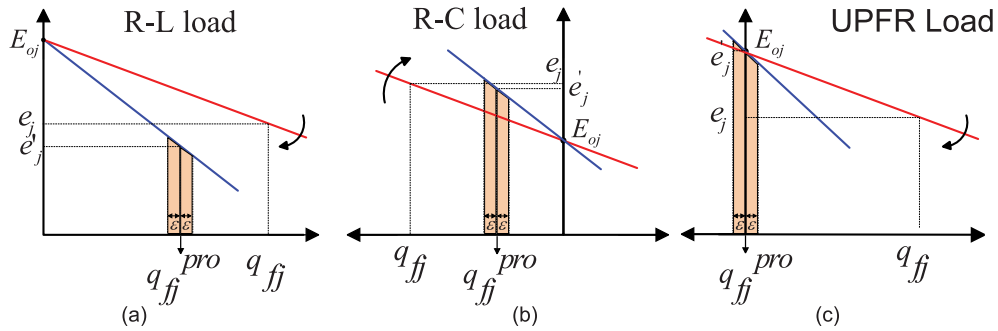


Fig. 3. Effect of PRPS controller on E – Q droop characteristics of jth source with R – L, R – C and UPFR load.

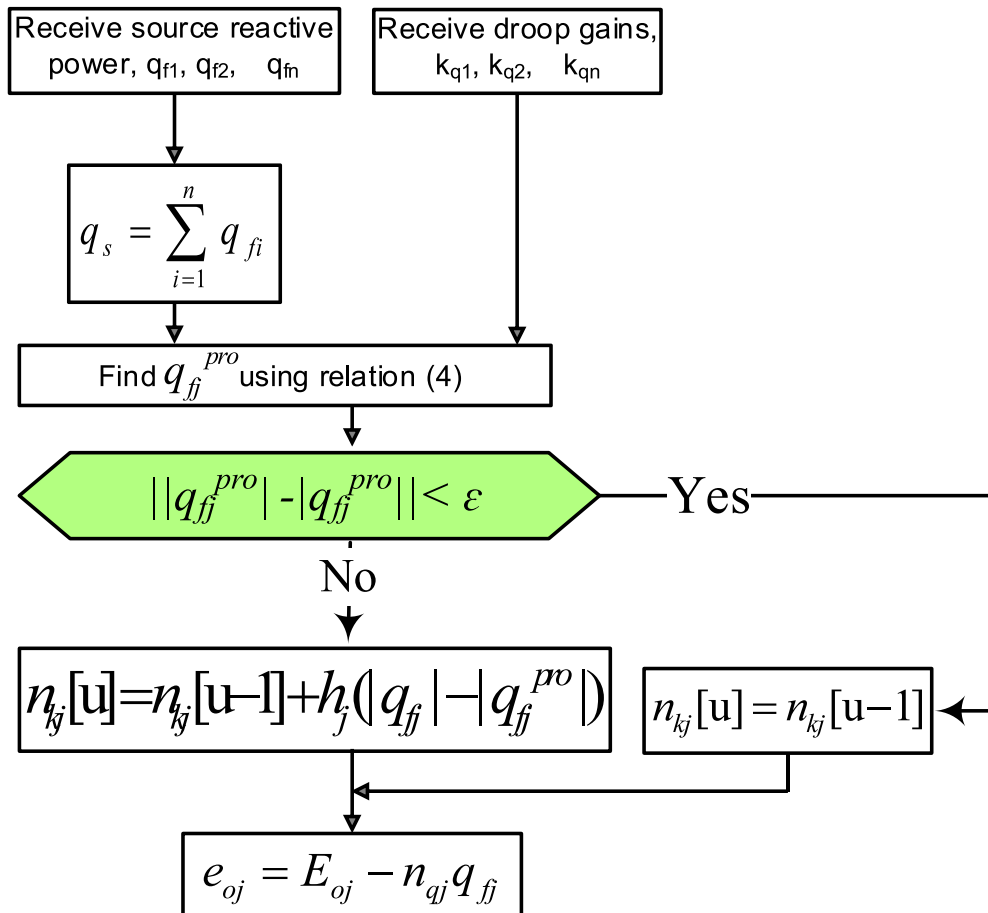


Fig. 4. Flow chart of IRPS controller.

current flowing between the source-*i* and source-*j* is given by

$$i_{ij} = \frac{e_i - e_j}{Z_{ij}} = \frac{E_i \angle \delta_i - E_j \angle \delta_j}{R_{ij} + jX_{ij}} \tag{8}$$

where, $\delta_{ij} = \delta_i - \delta_j$, is the phase angle difference between the source-*i* and source-*j*. The active power, p_{ij} and the reactive power, q_{ij} flowing between the source-*i* and source-*j* is expressed

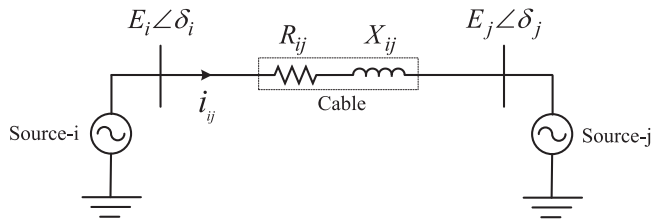


Fig. 5. Parallel operation of two sources.

using expression for apparent power, s_{ij} given by,

$$s_{ij} = p_{ij} + jq_{ij} = 3E_i \left(\frac{E_i \angle \delta_i - E_j \angle \delta_j}{R_{ij} + jX_{ij}} \right)^* \quad (9)$$

Here the symbol “*” in above expression denotes complex conjugate. Equating the real and imaginary parts, the expressions for p_{ij} and q_{ij} are,

$$p_{ij} = \frac{3E_i(E_i - E_j \cos \delta_{ij})R_{ij}}{R_{ij}^2 + X_{ij}^2} + \frac{3E_i E_j X_{ij}}{R_{ij}^2 + X_{ij}^2} \sin \delta_{ij} \quad (10)$$

$$q_{ij} = \frac{3E_i(E_i - E_j \cos \delta_{ij})X_{ij}}{R_{ij}^2 + X_{ij}^2} - \frac{3E_i E_j R_{ij}}{R_{ij}^2 + X_{ij}^2} \sin \delta_{ij} \quad (11)$$

In case of low voltage ac microgrid, from Table 1, the value of (R/X) ratio is 7.3. The inductance of cable can be neglected in comparison to resistance of cable. The modified expressions for p_{ij} and q_{ij} flowing between the source- i and source- j are,

$$p_{ij} = \frac{3E_i(E_i - E_j \cos \delta_{ij})}{R_{ij}} \quad (12)$$

$$q_{ij} = -\frac{3E_i E_j}{R_{ij}} \sin \delta_{ij} \quad (13)$$

For this case, the value of δ_{ij} is very small, therefore with this assumption, the modified expression for p_{ij} and q_{ij} are,

$$p_{ij} = \frac{3E_i(E_i - E_j)}{R_{ij}} \quad (14)$$

$$q_{ij} = -\frac{3E_i E_j}{R_{ij}} \delta_{ij} \quad (15)$$

For this case, the active power, p_{ij} is predominantly coupled with voltage difference, $E_i - E_j$ between the source- i and source- j , while the reactive power, q_{ij} is predominantly coupled with phase difference, δ_{ij} between the sources. The adjustment of active power affects the voltage difference between the sources and adjustment of reactive power affects the phase difference between the sources.

2.3. Sharing of reactive power with sources of unequal ratings

The secondary controller discussed in Shafiee et al. (2014) includes linear PI controller which uses average value of reactive powers supplied by sources. However, the performance of the suggested controller may deteriorate in case of ac microgrid having unequal ratings. However, the proposed PRPS controller ensures proportional sharing of reactive power even in case of ac microgrid having sources of unequal ratings.

To simplify the analysis, an ac microgrid including two sources is assumed. The rated values of reactive powers supplied by the sources are Q_1 and Q_2 receptively. Source-1 and source-2 supplies reactive power $q_{f1p.u.}$ and $q_{f2p.u.}$ with respect to their own bases. So, the total reactive power load demand of the system is $q_{f1p.u.}Q_1 + q_{f2p.u.}Q_2$ VAR. With average per-unit reactive power based controller, the reference values of reactive powers for both

Table 1
Parameters of cable (Engler and Sultanis, 2005).

Voltage level	R (Ω /km)	X (Ω /km)	R/X
High	0.06	0.191	0.31
Medium	0.161	0.19	0.85
Low	0.642	0.083	7.7

the sources are $(q_{f1p.u.} + q_{f2p.u.})/2$ which in their own bases become $((q_{f1p.u.} + q_{f2p.u.})/2 Q_1)$ VAR and $((q_{f1p.u.} + q_{f2p.u.})/2 Q_2)$ VAR. However, the total load demand is $q_{f1p.u.}Q_1 + q_{f2p.u.}Q_2$ VAR. The error between total load demand and total current commanded to both sources is $(q_{f1p.u.} - q_{f2p.u.})(Q_1 - Q_2)/2$ VAR. Therefore, average per-unit reactive power can lead to excess/less reactive power supplied by the sources. This is a major shortcoming of using average per-unit current.

Now using PRPS controller, the current reference generated for source-1 is given by,

$$Q_{1ref} = Q_1^{pro} = \frac{q_{f1p.u.}Q_1 + q_{f2p.u.}Q_2}{k_{q1}} \left(\frac{1}{\frac{1}{k_{q1}} + \frac{1}{k_{q2}}} \right) \quad (16)$$

Now using (3) for two sources, $k_{q1}Q_1 = k_{q2}Q_2 = k$. Therefore, $k_{q1} = k/Q_1$ and $k_{q2} = k/Q_2$. This helps us to simplify Q_{1ref} and Q_{2ref} as,

$$Q_{1ref} = \frac{q_{f1p.u.}Q_1 + q_{f2p.u.}Q_2}{Q_1 + Q_2} Q_1 \quad (17)$$

$$Q_{2ref} = \frac{q_{f1p.u.}Q_1 + q_{f2p.u.}Q_2}{Q_1 + Q_2} Q_2 \quad (18)$$

Addition of references for the total proportional reactive power is $q_{f1p.u.}Q_1 + q_{f2p.u.}Q_2$ VAR. Thus, total reactive power demanded by the load is exactly same as total reactive power supplied by the sources. This is true irrespective of the ratings and per-unit reactive power being supplied by the sources. Hence, using proportional per-unit reactive power sharing in place of average per-unit reactive power for the system having sources of unequal capacities will give good performance. The relation given by (16), (17) and (18) are also valid even for R – C and UPFR load. Therefore, the proposed secondary controller ensures accurate sharing of reactive power in case of R – C and UPFR loads.

Consider two sources, one has ratings as 500 kVAR, and the other one is rated 250 kVAR. These are supposed to supply a load of 650 kVAR. Initially, let the reactive power supplied by these sources be 400 kVAR and 250 kVAR due to transmission line resistances. Using proportional reactive power, the reference reactive powers set for the two sources as 443.33 kVAR and 216.67 kVAR which match the total reactive power demand. However, using the average per-unit reactive power, the reference values of reactive powers for the two sources are set as 450 kVAR and 225 kVAR. In this case, the total reactive power reference then will be 675 kVAR, which is more than the reactive power demanded by the load.

Similarly, if these two sources are supplying 450 kVAR and 200 kVAR, average per-unit current sets references of source-1 and source-2 as 425 kVAR and 212.5 kVAR. The total reactive power commanded is 637.5 kVAR which is less than the actual load demand. However, proportional reactive power reference, in this case, is the same as in the case above.

Further, as apparent from the above two examples, reference for per-unit average is dependent on the distribution of load which is not the case for proportional reactive power sharing controller. This is another drawback of the per-unit average. These two drawbacks make the Proportional Reactive Power Sharing (PRPS) controller more appealing than the per-unit average.

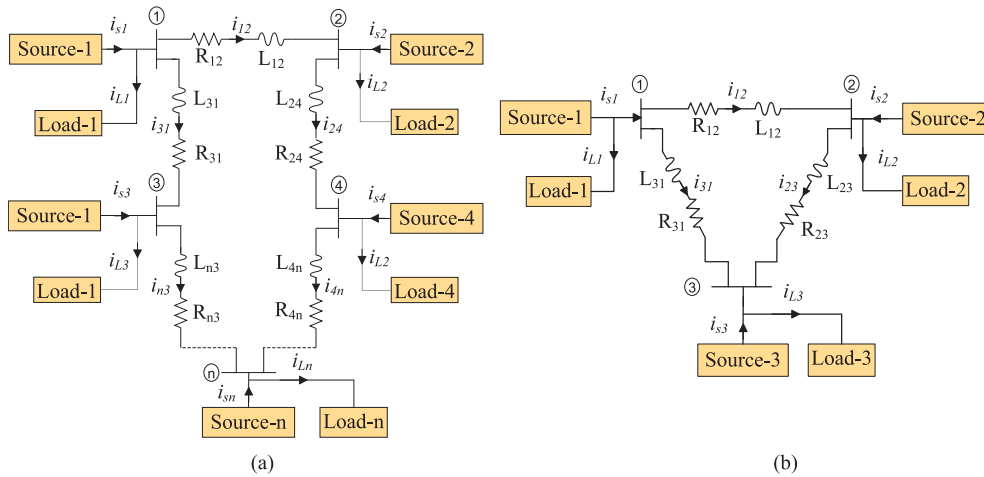


Fig. 6. Configurations of ac microgrid. (a) Ring network of ac microgrid with multiple sources and local loads. (b) Ring network of ac microgrid with three sources and local loads.

2.4. Use of low bandwidth communication channel

From (4), it is observed that the proportional value of reactive power, q_{ff}^{pro} to be supplied by j th source depends upon the initial values of droop gains, $k_{q1}, k_{q2} \dots k_{qn}$ of sources and the sum of reactive powers supplied by each source. The value of $k_{q1}, k_{q2} \dots k_{qn}$ remains fixed throughout the execution of control algorithm and the value of q_{fs} changes during step variation of load demand. The values of $k_{q1}, k_{q2} \dots k_{qn}$ once stored can be used for evaluation of proportional value of reactive power to be supplied by each source using (4). This justifies the use of low bandwidth communication channel.

3. Modeling of the proposed controller

In this section, the linearized reduced order model of ac microgrid using small signal relations is derived. The ring type network of ac microgrid including various sources and loads as shown in Fig. 6(a) is considered.

3.1. Source

In case of ac microgrid, the sources are interfaced to the ac bus of the microgrid using power electronic converters. A three-phase Voltage Source Inverter (VSI) is used to connect the ac source to ac microgrid which includes three loops to control its output active and reactive powers supplied by it. These loops are the inner voltage and current controllers and the outermost loop is the droop controller. These controllers are used to generate output ac voltage of desired magnitude and frequency. The d - q reference frame is widely used for the implementation of these loops which rotates at a frequency generated by $\omega - P$ droop control law when ac microgrid operates in the islanded mode of operation. The detailed modeling of the ac microgrid is elaborated taking into account the dynamics of sources, proposed controller, interconnecting lines, and loads. However, deriving the linearized model of ac microgrid, the dynamic of inner loop controllers like voltage and current controllers are neglected. It is because the dominant eigenvalues produced by these controllers are located far away from the imaginary axis (Pogaku et al., 2007). These eigenvalues have less impact on the dynamics of the ac microgrid. Therefore, a linearized reduced order model is used for the analysis of the performance of the PRPS controller.

The output voltage produced by i th source is e_i which is a complex variable inclined at an angle δ_i with d -axis, therefore

$e_i = \sqrt{e_{di}^2 + e_{qi}^2}$ and $\tan \delta_i = e_{qi}/e_{di}$. The linearized relations for e_i and δ_i using small signal approximation are expressed in matrix form as (Iyer et al., 2010),

$$\begin{bmatrix} \Delta e_d \\ \Delta e_q \end{bmatrix} = \begin{bmatrix} -E_{qo} & V_{do} \\ E_{do} & V_{qo} \end{bmatrix}_{2n \times 2n} \begin{bmatrix} \Delta \delta \\ \Delta e \end{bmatrix} = A_o \begin{bmatrix} \Delta \delta \\ \Delta e \end{bmatrix} \quad (19)$$

where, n is the number of sources connected in the microgrid, $V_{do} = E_{do}/V_o$, $V_{qo} = E_{qo}/V_o$ and $V_o = \sqrt{E_{do}^2 + E_{do}^2}$. Here, E_{do} and E_{qo} represent the values of d -axis voltage, e_{di} and q -axis voltage, e_{qi} about the equilibrium point. The values of rest of elements of (19) are $E_{do} = \text{diag}\{E_{do1}, E_{do2}, \dots, E_{don}\}$, $E_{qo} = \text{diag}\{E_{qo1}, E_{qo2}, \dots, E_{qon}\}$, $V_{do} = \text{diag}\{E_{do1}/\sqrt{E_{do1}^2 + E_{2qo1}}, E_{do2}/\sqrt{E_{2do2}^2 + E_{2qo2}}, \dots, E_{don}/\sqrt{E_{2don}^2 + E_{2qon}}\}$ and $V_{qo} = \text{diag}\{E_{qo1}/\sqrt{E_{2do1}^2 + E_{2qo1}}, E_{qo2}/\sqrt{E_{2do2}^2 + E_{2qo2}}, \dots, E_{qon}/\sqrt{E_{2don}^2 + E_{2qon}}\}$.

The conventional $\omega - P$ droop control law for j th source is given by

$$\omega_j = \omega_{oj} - k_{pj} p_{ff} \quad (20)$$

where, ω_j is the reference frequency generated by $\omega - P$ droop controller, ω_{oj} is the nominal value of frequency of j th source, k_{pj} is the droop gain of j th source and p_{ff} is the active power supplied by j th source. Linearizing above and writing in matrix form,

$$\Delta \omega = \Delta \delta = -k_p \Delta p_f \quad (21)$$

3.2. Interconnecting cables, loads and interconnecting network

The resistance and inductance of the cable connecting the i th and j th sources are R_{bij} and L_{bij} , respectively. By Kirchhoff's Voltage Law (KVL), the branch current i_{bij} and branch voltage e_{bij} are related by following relation,

$$L_{bij} \frac{di_{bij}}{dt} + R_{bij} i_{bij} = e_{bij} = e_i - e_j \quad (22)$$

Linearizing (22), transferring to d - q reference frame and replacing the values of $[\Delta e_d \ \Delta e_q]^T$ from (19),

$$\begin{bmatrix} \Delta \dot{i}_{bd} \\ \Delta \dot{i}_{bq} \end{bmatrix} = A_{b1} \begin{bmatrix} \Delta \delta \\ \Delta e \end{bmatrix} - A_{b2} \begin{bmatrix} \Delta i_{bd} \\ \Delta i_{bq} \end{bmatrix} + I_{bdq} [\Delta \omega] \quad (23)$$

where,

$$A_{b1} = L_b^{-1} M A_o, A_{b2} = \begin{bmatrix} L_b^{-1} R_b & -\omega \\ \omega & L_b^{-1} R_b \end{bmatrix}, I_{bdq} = \begin{bmatrix} I_{bqo} \\ -I_{bdo} \end{bmatrix}$$

Here, Matrix M is the incidence matrix of the network shown in Fig. 6(a). The dimensions of M is $m \times n$, with m as number

of branches and n number of buses. The elements, I_{bdo} and I_{bqo} represent the values of d -axis branch current, i_{bdi} and q -axis branch current, i_{bqi} about the equilibrium point.

A $R - L$ load is assumed to be connected at each source bus. The power drawn by $R - L$ load is

$$L_{lj} \frac{di_{lj}}{dt} + R_{lj} i_{lj} = e_j \quad (24)$$

Linearized relation for $R - L$ load is given by,

$$\begin{bmatrix} \Delta i_{ld} \\ \Delta i_{lq} \end{bmatrix} = A_{L1} \begin{bmatrix} \Delta \delta \\ \Delta e \end{bmatrix} - A_{L2} \begin{bmatrix} \Delta i_{ld} \\ \Delta i_{lq} \end{bmatrix} + I_{Ldq} [\Delta \omega] \quad (25)$$

where,

$$A_{L1} = L_L^{-1} A_o, A_{L2} = \begin{bmatrix} L_L^{-1} R_L & -\omega \\ \omega & L_L^{-1} R_L \end{bmatrix}, I_{Ldq} = \begin{bmatrix} I_{Lqo} \\ -I_{Ldo} \end{bmatrix}$$

The elements, I_{Ldo} and I_{Lqo} represent the values of d -axis load current, i_{Ldi} and q -axis branch current, i_{Lqi} about the equilibrium point.

By applying Kirchhoff's current law, in the circuit shown in Fig. 6(a), at any source bus, the source current vector i_s , load current i_L and branch current i_b are related as,

$$i_s - i_L = M^T i_b \quad (26)$$

Transferring (26) to synchronously rotating reference frame,

$$\begin{bmatrix} \Delta i_{sd} \\ \Delta i_{sq} \end{bmatrix} = \begin{bmatrix} \Delta i_{ld} \\ \Delta i_{lq} \end{bmatrix} + \begin{bmatrix} M^T & 0 \\ 0 & M^T \end{bmatrix} \begin{bmatrix} \Delta i_{bd} \\ \Delta i_{bq} \end{bmatrix} \quad (27)$$

3.3. Calculation for filtered power

Instantaneous values of real power p_j and reactive power q_j supplied by j th source, are given by $p_j = e_{dj} i_{sdj} + e_{qj} i_{sqj}$ and $q_j = e_{dj} i_{sqj} - e_{qj} i_{sdj}$. By linearizing above relations and substituting $[\Delta e_d \ \Delta e_q]^T$ and $[\Delta i_{sd} \ \Delta i_{sq}]^T$ from (19) and (27),

$$\begin{bmatrix} \Delta p \\ \Delta q \end{bmatrix} = I_{sdqo} A_o \begin{bmatrix} \Delta \delta \\ \Delta e \end{bmatrix} + E_{dqo} M^T \begin{bmatrix} \Delta i_{bd} \\ \Delta i_{bq} \end{bmatrix} + E_{dqo} \begin{bmatrix} \Delta i_{ld} \\ \Delta i_{lq} \end{bmatrix} \quad (28)$$

where,

$$I_{sdqo} = \begin{bmatrix} I_{sdo} & I_{sqo} \\ I_{sqo} & -I_{sdo} \end{bmatrix}, E_{sdqo} = \begin{bmatrix} E_{do} & E_{qo} \\ -E_{qo} & E_{do} \end{bmatrix}$$

The elements, I_{sdo} and I_{sqo} represent the values of d -axis source current, i_{sdi} and q -axis branch current, i_{sqi} about the equilibrium point.

The average values of active, p_{fj} and reactive powers, q_{fj} are expressed as

$$\frac{p_{fj}}{dt} = -\omega_c p_{fj} + \omega_c p_j \quad (29)$$

$$\frac{q_{fj}}{dt} = -\omega_c q_{fj} + \omega_c q_j \quad (30)$$

where, ω_c represents cut-off frequency of first order low pass filter. Linearizing above relations and replacing the values of $[\Delta p \ \Delta q]^T$ from (28),

$$\begin{bmatrix} \Delta p_{fj} \\ \Delta q_{fj} \end{bmatrix} = \omega_c I_{sdqo} A_o \begin{bmatrix} \Delta \delta \\ \Delta e \end{bmatrix} - \omega_c \begin{bmatrix} \Delta p_{fj} \\ \Delta q_{fj} \end{bmatrix} + \omega_c E_{dqo} M^T \begin{bmatrix} \Delta i_{bd} \\ \Delta i_{bq} \end{bmatrix} + \omega_c E_{dqo} \begin{bmatrix} \Delta i_{ld} \\ \Delta i_{lq} \end{bmatrix} \quad (31)$$

3.4. PRPS controller

The instantaneous value of n_{kj} generated by secondary controller is supplied to the $Q - E$ droop controller. The dynamical equation governing its behavior is given by,

$$\frac{dn_{qj}}{dt} = \frac{h_j}{\tau} (q_{fj} - q_{fj}^{pro}(t - \tau)) \quad (32)$$

where, $q_{fj}^{ideal}(t - \tau)$ is the communicated value of proportional reactive power and τ is the time delay caused due to low bandwidth communication channel. Writing above in matrix form for an microgrid having multiple sources,

$$\frac{dn_q}{dt} = \frac{H}{\tau} q_f - \frac{HW}{\tau} q_f(t - \tau) \quad (33)$$

Here, W is a matrix used to calculate proportional reactive power from total reactive power. Linearizing (33) using small signal approximation,

$$\frac{d\Delta n_{qj}}{dt} = \frac{h_j}{\tau} (\Delta q_{fj} - \Delta q_{fj}^{pro}(t - \tau)) \quad (34)$$

The linearized value of $\Delta q_{fj}^{pro}(t - \tau)$ calculated from (4) is

$$\Delta q_{fj}^{pro}(t - \tau) = w_j \Delta q_{fs}(t - \tau) \quad (35)$$

where, $w_j = k_{qs}/k_{qj}$. The linearized value of $\Delta q_s(t - \tau)$ calculated from (3) is

$$\begin{aligned} \Delta q_{fs}(t - \tau) &= \Delta q_{f1}(t - \tau) + \Delta q_{f2}(t - \tau) + \dots + \Delta q_{fn}(t - \tau) \\ &= \sum_{i=1}^n \Delta q_{fi}(t - \tau) \end{aligned} \quad (36)$$

From (35) and (36), the communicated value of $\Delta q_{fj}^{pro}(t - \tau)$ is

$$\Delta q_{fj}^{pro}(t - \tau) = w_j \sum_{i=1}^n \Delta q_{fi}(t - \tau) \quad (37)$$

Substituting the value of $\Delta q_{fj}^{pro}(t - \tau)$ in (26) and simplifying,

$$\frac{d\Delta n_{qj}}{dt} = \frac{h_i}{\tau} \Delta q_{fj} - w_j \sum_{i=1}^n \Delta q_{fi}(t - \tau) \quad (38)$$

Writing above in matrix form,

$$\frac{dn_{qj}}{dt} = \frac{H}{\tau} \Delta q_f - \frac{HW}{\tau} \Delta q_f(t - \tau) \quad (39)$$

where, \mathbf{M} is the matrix to calculate ideal reactive power from total reactive power q_{fs} and is given by,

$$\mathbf{W} = \begin{bmatrix} w_1 & w_1 & \dots & w_1 \\ w_2 & w_2 & \dots & w_2 \\ \vdots & \vdots & \ddots & \vdots \\ w_n & w_n & \dots & w_n \end{bmatrix}$$

To derive the linearized model of ac microgrid, the state equations given by (21), (23), (25), (31), and (39) are converted into the standard state variable form, $\Delta \dot{x} = A \Delta x + B \Delta u$. The generalized time delayed state space model of ac microgrid is written as,

$$\Delta \dot{x}_{mg} = A_{mgo} \Delta x_{mg}(t) + A_{mgs} \Delta x_{mg}(t - \tau) \quad (40)$$

where,

$$\Delta x_{mg} = [\Delta \delta \ \Delta p_f \ \Delta q_f \ \Delta i_{bdq} \ \Delta i_{ldq} \ \Delta n_q] ,$$

Here, $A_{mgo} = R_s^{-1} A_s$, $A_{mgs} = R_s^{-1} A_{sd}$, and $\Delta x_{mg}(t - \tau)$ represents the time delayed states of the system and A_{mgs} is the system matrix

$$A_s = \begin{bmatrix} 0 & -k_p & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \omega_c Q_o & -\omega_c & -\omega_c \frac{P_o}{V_o} & \omega_c E_{do} M^T & \omega_c E_{qo} M^T & \omega_c E_{do} & \omega_c E_{qo} & \omega_c \frac{P_o}{V_o} Q_o & 0 \\ -\omega_c P_o & 0 & -\omega_c (I + N_{qo} \frac{Q_o}{V_o}) & -\omega_c E_{qo} M^T & \omega_c E_{do} M^T & -\omega_c E_{qo} & \omega_c E_{do} & -\omega_c \frac{Q_o}{V_o} & 0 \\ 0 & 0 & L_b^{-1} M N_{qo} & -L_b^{-1} R_b & L_b^{-1} \omega_o & 0 & 0 & -L_b^{-1} M Q_o & 0 \\ 0 & 0 & L_b^{-1} M N_{qo} & -L_b^{-1} \omega_o & -L_b^{-1} R_b & 0 & 0 & -L_b^{-1} M Q_o & 0 \\ 0 & 0 & L^{-1} N_{qo} & 0 & 0 & -L_L^{-1} R_L & L_L^{-1} \omega_o & -L_L^{-1} Q_o & 0 \\ 0 & 0 & L_L^{-1} N_{qo} & 0 & 0 & -L_L^{-1} \omega & -L_L^{-1} R_L & -L_L^{-1} Q_o & 0 \\ 0 & 0 & \frac{H}{\tau} & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad (42)$$

Box 1.

Table 2
Parameters of test system.

Parameter	Symbol	Value
Cable resistance and inductance (per km)	R_b, L_b	0.386 Ω , 150 μ H
Cable lengths		1000 m, 1250 m, 1500 m
Inverter Switching frequency	f_s	5 kHz
Nominal values of inverter output voltages	E	230 V, 230 V, 230 V
RLC filter of inverter	ESR_L, L, C	0.02 Ω , 1.1 mH, 300 μ F
Nominal line frequency	f_o	50 Hz
Cut off frequency of low pass filter	f_c	7 Hz
P-f droop gain	K_p	0.0000625 rad/s-W
Q-E droop gain	K_q	0.000115 V/VAr
Power rating of inverter	S	100 kVA
Power rating of UPFR	P_L	90 kW
Input inductance of UPFR	ESR_L, L	0.02 Ω , 1 mH
DC output capacitance of UPFR	C_o	5 mF
Load resistance of active rectifier	R_o	4.5 Ω

corresponding to delayed states. The values of matrices A_s, A_{sd} and R_s are given by,

$$A_{sd} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{HW}{\tau} & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad (41)$$

A_s given in Box 1.

$$R_s = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ I_{bqo} & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ -I_{bdo} & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ I_{Lqo} & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ -I_{Ldo} & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad (43)$$

4. Simulation results and discussion

To verify the proposed technique, detailed simulation and analytically studies are carried out and results are included in this section. A ring configuration of ac microgrid with local loads

connected at each sources bus is considered as shown in Fig. 6(b). The parameters of the microgrid considered for analysis are given in Table 2.

4.1. Effect of delay on the stability of the system

In this paper, single and constant time delay is assumed among all the communications links used by the PRPS based secondary controller. In this section, the effect of time delay on the stability of the system is explored. The analysis is carried out to evaluate an upper bound on the delay, τ_d of the system beyond which the operation of the system becomes unstable. For this purpose, the eigenvalues of the system are determined by evaluating the roots of the characteristic equation. From (40), the characteristic equation for the time delayed system is given by,

$$\phi(\lambda, \tau) = \lambda I_o - A_{mgo} - A_{mgs} e^{-\lambda \tau} \quad (44)$$

where, I_o is an identity matrix of the order of n and λ represent the roots of characteristic equations. The above characteristics equation for time delayed system is transcendental in nature and has infinite number of roots. However the effect of time delay on system is studied by evaluating reduced set of roots. The effective roots of system are approximated using finite element method reported in Milano and Anghel (2012) and Liu et al. (2015). The matrix which provides the reduced set of poles of the system is given by following expression,

$$\phi = \begin{bmatrix} \hat{C} \otimes I_o & & \\ A_{mgs} & 0 & A_{mgo} \end{bmatrix} \quad (45)$$

where, \otimes represent Kronecker's product. Matrix \hat{C} consists of the first M rows of matrix C which is defined as

$$C = -2D_M/\tau \quad (46)$$

where, D_M is a matrix of order $(M + 1) \times (M + 1)$ and called as Chebyshev's differentiation matrix. The details of matrix, D_M is discussed in detail in Milano and Anghel (2012).

The effect of time delay on the performance of proposed droop control technique is studied with the help of eigenvalues root loci plot shown in Fig. 7. The value of time delay, τ is varied from 0 s to 200 ms. It is observed that for the communication delay of 100 ms, the movement of eigenvalues takes place from left half plane (LHP) into the right half plane (RHP). The microgrid system becomes unstable for value of time delay of 100 ms. Therefore, the value of delay margin, τ_d for the ac system with PRPS controller is 100 ms.

To validate the efficacy of the proposed controllers, the simulation and analytical studies of ac microgrid are carried out in Matlab/Simulink and the captured results are included in this subsection. A three bus system with three sources and local loads connected across each source bus as shown in Fig. 6(b) is considered. The parameters of the microgrid considered for analysis

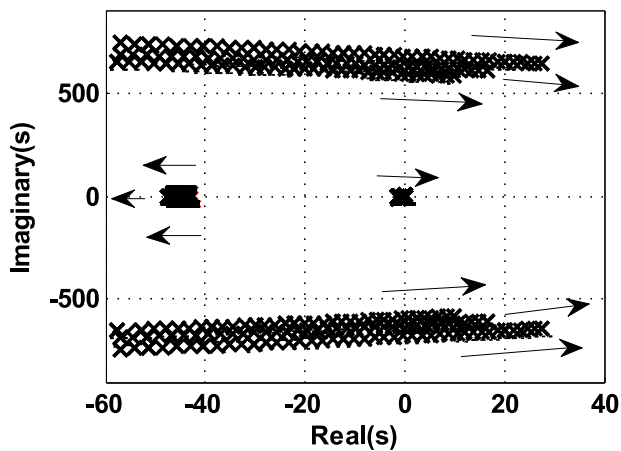


Fig. 7. Root loci plot of eigenvalues with variation in time delay, τ .

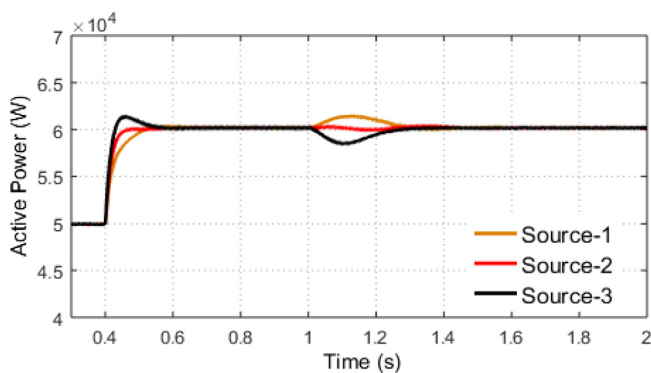


Fig. 8. Waveforms of active power supplied by sources for $R-L$ load.

are given in Table 1. The power rating of source-1, source-2 and source-3 are 100 kVA each and the rated voltage is $V_b = 400$ V. The active power droop gains, k_{p1} , k_{p2} and k_{p3} of source-1, source-2 and source-3 are selected for frequency regulation of 2% at full load while the reactive power droop gains k_{q1} , k_{q2} and k_{q3} of source-1, source-2 and source-3 are selected for voltage regulation of 5% at full load. The local loads, load-1, load-2 and load-3 are connected across each bus.

4.2. Validation of PRPS controller in ac microgrid with sources of equal capacities

In this subsection, the validation of the proposed PRPS controller is carried out for ac microgrid having sources with identical power ratings. The comparison between the conventional and proposed PRPS controller is carried out to show the efficacy of the proposed PRPS controller. The performance of the controller is studied with the effect of unequal local loads connected across each source. Sources are connected in the ring network shown in Fig. 6(b) through interconnecting lines having unequal values of line impedances. The performance of PRPS controller is observed for ac microgrid having $R-L$, $R-C$ and UPFR loads connected across each bus.

4.2.1. Validation for $R-L$ load

In this subsection, the validation for the performance of the PRPS controller is carried out for the resistive+inductive ($R-L$) load. The Fig. 8 shows the waveform of active powers, P_1 , P_2 and P_3 supplied by the source-1, source-2 and source-3, respectively. Before time instant, $t = 0.4$ s, the power demanded by the loads

connected at bus-1, bus-2 and bus-3 are 50 kW and 30 KVAR, respectively. At time instant, $t = 0.4$ s, a step variation in load demand from 50 kW, 30 KVAR to 60 kW, 40 KVAR at bus-2 and 50 kW, 30 KVAR to 70 kW, 50 KVAR at bus-3 is applied. Due to action of conventional $\omega - P$ droop control law given by (12), source-1, source-2 and source-3 supplies active power, P_1 , P_2 and P_3 in proportion to their ratings. The active power supplied by each source is 60 kW as shown in Fig. 8. This ensures that the conventional $\omega - P$ droop control law given by (20) is able to ensure the proportional sharing of active power demanded by loads among the sources.

However, due to unequal loads connected across each source bus and unequal voltage drops taking place across interconnecting lines, the performance of the conventional $E - Q$ droop law given by Eq. (1) deteriorates and the sources do not supply reactive powers in proportion to their ratings. In this case the ideal value of reactive power to be supplied by each source evaluated using (4) is 40 KAr. However, the reactive power supplied by source-1, source-2 and source-3, Q_1 , Q_2 and Q_3 are 25 kVAR, 40 kVAR and 55 kVAR, respectively as shown in Fig. 9(a). To ensure proportional sharing of reactive power, the proposed PRPS controller given by (7) is switched on at time $t = 1$ s. The value of ε , in this case is 0.5%. The value of communication delay maintained here is 1 ms. The control action of the PRPS controller modifies the droop gains of n_q of source-1, source-2 and source-3 and forces them to share power in proportion to their ratings. At time $t = 1.4$ s, the reactive power supplied by source-1, source-2 and source-3 is converged to its ideal value which is 40 KAr. Figs. 9(b) and 9(c) shows the waveforms of variation in $E - Q$ droop gains, n_{q1} , n_{q2} and n_{q3} and voltages of source-1, source-2 and source-3. From these waveforms, it is observed that reactive power sharing accuracy due to conventional $E - Q$ droop law is 37.5% (source-1) while in case of distributed PRPS controller, the error in reactive power sharing accuracy is reduced to 0.25%. The proposed distributed secondary controller ensures convergence of reactive power supplied by each source to its proportional value of reactive power. The value of voltage regulation maintained across each source converter is less than 5%.

4.2.2. Validation for $R-C$ load

In this case, the performance of the proposed PRPS controller is observed for $R-C$ load connected across each source bus. Before time instant, $t = 0.4$ s, the power demanded by the loads connected at bus-1, bus-2 and bus-3 are 50 kW and -30 KVAR, respectively. At time instant, $t = 0.4$ s, a step variation in load demand from 50 kW, -30 KVAR to 60 kW, -40 KVAR at bus-2 and 50 kW, -30 KVAR to 70 kW, -50 KVAR at bus-3 is applied. In this case, the value of ε is 0.5%. The value of communication delay maintained here is 1 ms. Figs. 9(d), 9(e) and 9(f) show the waveform of reactive powers, Q_1 , Q_2 and Q_3 , $E - Q$, droop gains, n_{q1} , n_{q2} and n_{q3} and voltages of source-1, source-2 and source-3. In this case the ideal value of reactive power to be supplied by each source evaluated using (4) is -40 KAr. However, the reactive power supplied by source-1, source-2, and source-3, Q_1 , Q_2 , and Q_3 are -29 KVAR, -40 KVAR, and -51 KVAR, respectively as shown in Fig. 9(d). To ensure proportional sharing of reactive power, the proposed PRPS controller given by (7) is switched on at time $t = 1$ s. The control action of the PRPS controller modifies the droop gains of n_q of source-1, source-2, and source-3 and forces them to share power in proportion to their ratings. At time $t = 1.4$ s, the reactive power supplied by source-1, source-2, and source-3 is converged to its ideal value which is -40 KAr. In this case, the error in reactive power sharing] using conventional $E - Q$ droop law is -27.5% while in case of distributed PRPS controller, the error in reactive power sharing accuracy is reduced to 0.75%. The value of voltage regulation maintained across each source converter is less than 5%.

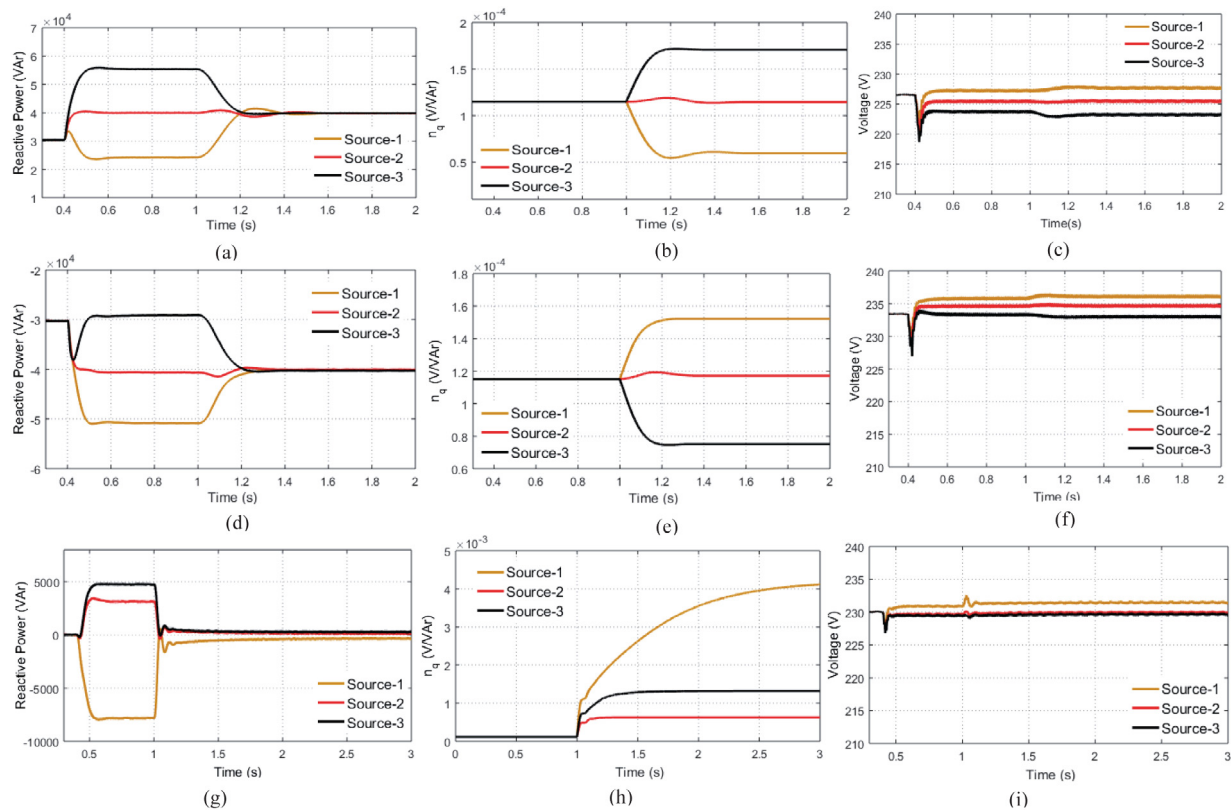


Fig. 9. Response of ac microgrid for $R-L$ load. (a) Waveforms of reactive power supplied by source-1, source-2 and source-3. (b) Waveform of $E-Q$ droop gains, n_{q1} , n_{q2} and n_{q3} and (c) Waveforms of voltages of source-1, source-2 and source-3. Response of ac microgrid for $R-C$ load. (d) Waveforms of reactive power supplied by source-1, source-2 and source-3. (e) Waveform of $E-Q$ droop gains, n_{q1} , n_{q2} and n_{q3} and (f) Waveforms of voltages of source-1, source-2 and source-3. Response of ac microgrid for UPFR load. (g) Waveforms of reactive power supplied by source-1, source-2 and source-3. (h) Waveform of $E-Q$ droop gains, n_{q1} , n_{q2} and n_{q3} and (i) Waveforms of voltages of source-1, source-2 and source-3.

4.2.3. Validation for UPFR load

In this case, the performance of the proposed PRPS controller is observed for UPFR load connected across each source bus. Before time instant, $t = 0.4$ s, the active and reactive power demanded by each load connected at bus-1, bus-2, and bus-3 is 50 kW and 0 KVAR, respectively. At time instant, $t = 0.4$ s, a step variation in load demand from 50 kW to 60 kW at bus-2 and 50 kW to 65 kW at bus-3 is applied. In this case, the value of ε is 0.5%. The value of communication delay maintained here is 1 ms. In this case the ideal value of reactive power to be supplied by each source evaluated using (4) is 0 KAr. However, from Fig. 9(g), it is observed that due to action of $E-Q$ droop law, the reactive power supplied by source-1, source-2 and source-3 are 5 KVAR, 3 KVAR and -8 KVAR, respectively. These are the circulating reactive powers, Q_1 , Q_2 and Q_3 which start flowing among sources. Source-1 is supplying reactive power of 8 KVAR and source-2 and source-3 are consuming the reactive powers of 3 KVAR and 5 KVAR. To minimize these circulating reactive powers, the PRPS controller is switched on at time $t = 1$ s which minimizes the values of circulating reactive powers, Q_1 , Q_2 , and Q_3 . Since the value of circulating reactive power consumed by source-2 and source-3 is small as compared to source-1. Therefore, the change in the value of droop gain, n_q of source-1 will be larger as compared to source-2 and source-3. Figs. 9(h) and (9)(i) show the waveform of $E-Q$ droop gains, n_{q1} , n_{q2} and n_{q3} and voltages of source-1, source-2 and source-3. In this case, the error in reactive power sharing using conventional $E-Q$ droop law is -8% while in the case of distributed PRPS controller, the error in reactive power sharing accuracy is reduced to -0.5% . The value of voltage regulation is maintained across each source converter is less than 5%.

4.3. Performance of the PRPS controller with nonlinear loads connected in ac microgrid

To validate the performance of the PRPS controller with nonlinear loads, the $R-L$ load connected at bus-1 is replaced by a three-phase bridge rectifier. At time $t = 0$ s, the initial demand of the rectifier is 10 kW. At time instant, $t = 0.4$ s, the load demand of the bridge rectifier is increased to 20 kW. Before time instant, $t = 0.4$ s, the power demanded by the loads connected at bus-2 and bus-3 are 50 kW and 30 KVAR, respectively. At time instant, $t = 0.4$ s, a step variation in load demand from 50 kW, 30 KVAR to 60 kW, 40 KVAR at bus-2 and 50 kW, 30 KVAR to 70 kW, 50 KVAR at bus-3 is applied. Figs. 10(a) and 10(b) show the waveform of active and reactive powers supplied by source-1, source-2, and source-3. The conventional $E-Q$ droop control law is used to ensure proportional sharing of average values of active and reactive powers. Therefore, the performance of the PRPS controller remains unaffected even in presence of nonlinear loads. A drop in the value of active power is observed which occurs due to a decrease in the value of source voltage caused by the PRPS controller. Fig. 10(c) shows the waveform of line current drawn by the three-phase bridge rectifier connected at bus-1. Fig. 10(d) shows the waveforms of output voltage, current, and power demanded by the rectifier. Fig. 10(d) shows the waveform of line current.

The harmonic current will be shared by the all the sources connected the ac microgrid. However, the convention droop control laws which are $\omega-P$ and $E-Q$ are primarily used to ensure proportional sharing of the fundamental component of active and reactive power. These controllers are used to share the average value of active and reactive power and the harmonic

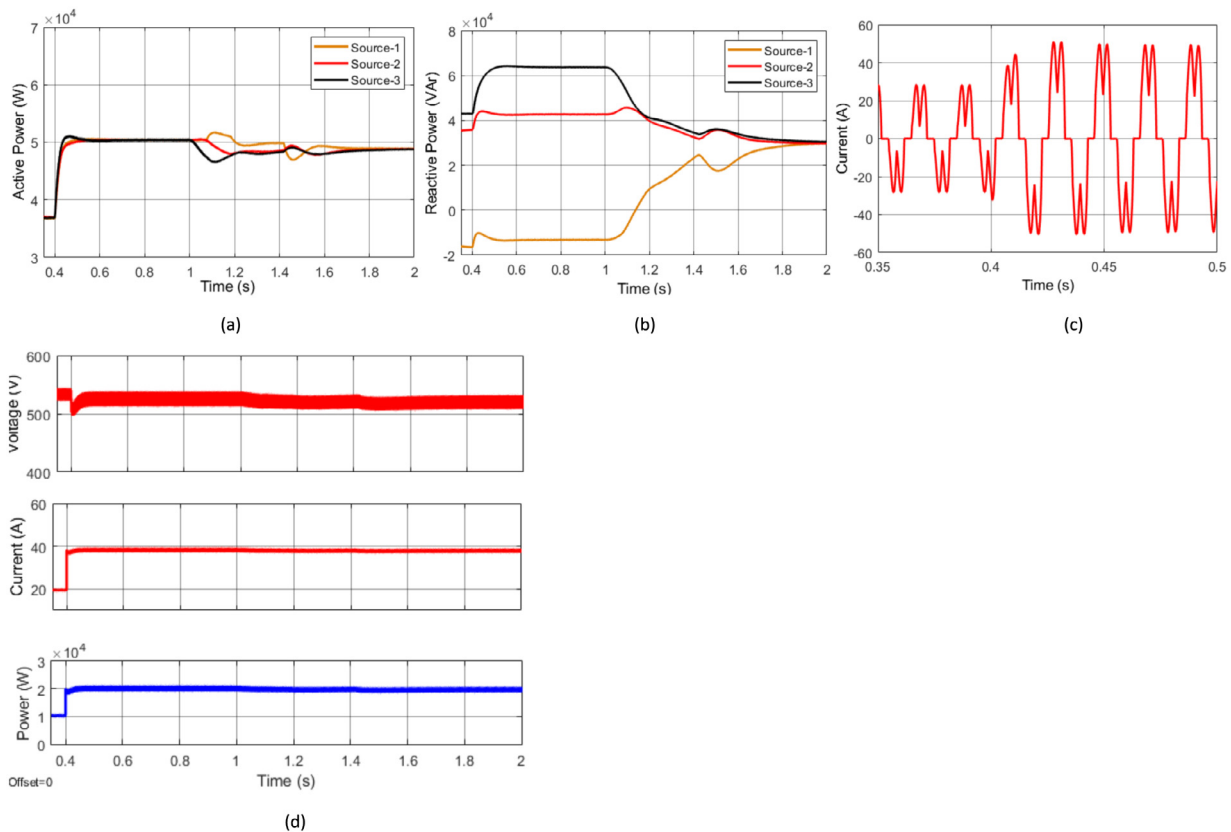


Fig. 10. Response of ac microgrid for sources with rectifier load. (a) Waveforms of active power supplied by the source-1, source-2, source-3. (b) Waveforms of reactive power supplied by the source-1, source-2, source-3. (c) Waveform of line current. (d) Waveform of output voltage, current and power demanded by the rectifier load.

current sharing is not ensured. Therefore, more harmonics will be observed in the three-phase currents supplied by the source-1 as compared to the three-phase currents supplied by source-2 and source-3. To validate this, three-phase currents supplied by the source-1, 2 and 3 are shown in Fig. 11. From the waveforms shown in Figs. 11(a), 11(b) and 11(c), it is observed that the harmonic contents in three-phase currents of source-1 are more as compared to source-2 and source-3 currents.

4.4. Validation of PRPS controller in ac microgrid with sources of unequal capacities

In this subsection, the validation of the proposed PRPS controller is carried out for ac microgrid having sources with unequal power ratings. The comparison between the conventional and proposed PRPS controller is carried out to show the efficacy of the proposed PRPS controller. The performance of the controller is studied with the effect of unequal local loads connected across each source. The sources are connected in the ring network shown in Fig. 6(b) through interconnecting lines having unequal values of line impedances. The performance of PRPS controller is observed for ac microgrid having $R-L$ loads connected across each bus.

In this case, the value of ε in this case is 0.5%. The value of communication delay maintained here is 1 ms. The ratings of sources connected at bus-1, bus-2 and bus-3 are 100 kVA, 75 kVA and 50 kVA. The load connected at bus-1, bus-2 and bus-3 are [50 kW, 40 kVAr], [30 kVAr, 20 kVAr] and [20 kW, 10 kVAr], respectively. Fig. 12(a) shows the waveforms of reactive powers supplied by source-1, source-2 and source-3. The reactive powers supplied by the source-1, source-2, and source-3 are 40 KVAR, 15 KVAR, and 15 KVAR, respectively. However, in this case, the

ideal values of reactive powers to be supplied by the source-1, source-2, and source-3 evaluated using (4) are 31.1 KAr, 23.4 KVAR, and 15.5 KVAR, respectively. To ensure proportional sharing of reactive power, the proposed PRPS controller given by (7), the proposed PRPS controller is switched on at time instant $t = 1$ s. The control action of the PRPS controller modifies the droop gains of n_q of source-1, source-2, and source-3 and forces them to share power in proportion to their ratings. At time $t = 1.4$ s, the reactive power supplied by source-1, source-2, and source-3 is converged to their ideal values which are 31.1 KAr, 23.4 KVAR, and 15.5 KVAR, respectively. Figs. 12(b) and (12)(c) show the waveform of n_{q1} , n_{q2} and n_{q3} and voltages of source-1, source-2 and source-3.

In this case, the error in reactive power sharing accuracy using conventional $E-Q$ droop law is 8% while in the case of distributed PRPS controller, the reactive power sharing accuracy is 0.5%. The value of voltage regulation is maintained across each source converter is less than 5%.

Table 3 shows the error in reactive power-sharing with conventional $E-Q$ droop law and distributed secondary PRPS controller for R-L, R-C, and UPFR types of local loads connected at the bus-1, bus-2, and bus-3 of ac microgrid having sources of equal capacities. Table 4 shows the error in reactive power-sharing with conventional $E-Q$ droop law and distributed secondary PRPS controller for R-L types of local loads connected at the bus-1, bus-2, and bus-3 when sources of unequal capacities are connected in ac microgrid. The low values of errors in reactive power sharing validate the efficacy of the proposed distributed secondary controller to ensure proportional sharing of reactive power in case of ac microgrid having sources of unequal capacities, mismatching in interconnecting line impedances, and local loads having unequal active and reactive power demands.

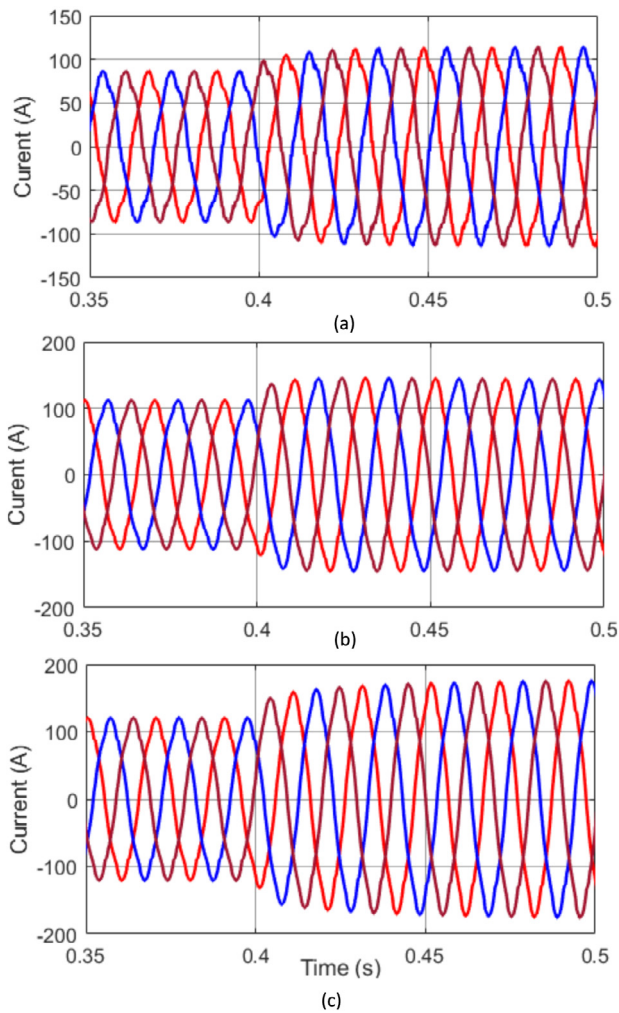


Fig. 11. Performance of the proportional reactive power sharing (IRPS) controller in ac microgrid with nonlinear load. (a) Current supplied by source-1. (b) Current supplied by source-2. (c) Current supplied by source-3.

4.5. Effect of variation in time delay

In this subsection, the effect of variation of time delay in communication on the response of ac microgrid including PRPS controller is observed. In this case, loads demands maintained at sources buses are the same as that of the $R - L$ load case considered in the previous subsection. Figs. 12(d), (12)(e), and (12)(f) show the response of the ac microgrid for time delays of 10 ms, 100 ms and 500 ms. From these figures, it is observed that the response of the system becomes oscillatory for increasing values of time delays in communication. For a delay time of $\tau = 100$ ms, bounded oscillations are observed in the response of ac microgrid with PRPS controller. For the value of time delay, $\tau = 500$ ms, the response of the ac microgrid becomes unstable. The delay margin of the ac microgrid evaluated in subsection-A of this section is evaluated to be 100 ms. The operation of ac microgrid for these values of time delays is in close agreement.

4.6. Comparison of PRPS controller with the controller suggested in Shafiee et al. (2014)

In this section, the performance of the proposed PRPS controller is compared with the controller suggested in Shafiee et al. (2014). Fig. 13(a) shows the waveforms of the total reactive

Table 3

Comparison of reactive power sharing accuracy and voltage regulation using conventional $E - Q$ droop and proposed PRPS controllers.

Source	Load	Reactive power Sharing accuracy		Voltage regulation	
		Conventional	Proposed	Conventional	Proposed
1	R-L	37.5%	0.25%	1.1%	1.30%
		0.5%	0.30%	1.95%	1.73%
		-40%	0.50%	2.82%	3.04%
1	R-C	-27.5%	0.75%	-2.82%	-3.04%
		2.5%	-1.25%	-2.17%	-2.25%
		27.5%	0.50%	-1.74%	-1.52%
1	UPFR	-8.0%	-0.5%	0.8%	0.85%
		3.0%	0.25%	0.2%	0.15%
		5.0%	0.25%	0.2%	0.15%

Table 4

Comparison of reactive power sharing accuracy and voltage regulation for ac microgrid having sources of unequal capacities.

Source	Load	Reactive power Sharing accuracy		Voltage regulation	
		Conventional	Proposed	Conventional	Proposed
1	R-L	51%	0.96%	0.8%	0.4%
		-66%	-1.1%	3.2%	3.15%
		0.2%	0.25%	1.30%	1.10%

power supplied by the source-1, source-2, and source-3 and the total reactive power demanded by the load-1, load-2 and load-3 using the PRPS controller. Fig. 13(b) shows the waveforms of the total reactive powers supplied by the source-1, source-2, and source-3 and the reactive power demanded by the load-1, load-2 and load-3 using the controller suggested in Shafiee et al. (2014). From the waveforms shown in Fig. 13(a), it is observed that in the case of the proposed controller, the reactive power supplied by the sources and that demanded by the loads are in close agreement. However, in the case of the controller suggested in Shafiee et al. (2014), there exists a significant difference between the reactive power supplied by sources and the reactive power demanded by the loads. This is shown in Fig. 13(b).

5. Conclusion

In this paper, to ensure proportional sharing of reactive power, a distributed PRPS controller is proposed. The validation of the proposed controller is carried out for islanded mode of operation of ac microgrid. The salient feature of the proposed controller is that it ensures an accurate degree in reactive power sharing in case of ac microgrid having sources of unequal capacities. For this purpose, the controller compares the actual reactive power with its proportional value of reactive power to be supplied by each source in the ac microgrid. Depending upon the difference between the two values, the proposed controller modifies the slope of $Q - E$ droop characteristics in such a way that each source supplies power in proportion to its rated capacity. To validation for the efficacy of the PRPS controller, the simulation studies in Matlab/Simulink are carried out for an ac microgrid. The ac microgrid includes sources of unequal values of rated capacities with unequal local loads connected at their ends and connected with each other through interconnecting lines having mismatching in impedances values. The controller compares the reactive power with its proportional value and ensures convergence to it. Depending upon the value of ϵ , the desired degree of accuracy in reactive power-sharing is ensured. In the case of ac microgrid having $R - L$, the error in reactive power sharing accuracy is 37.5%. However, the proposed controller reduces the error in reactive power-sharing from 37.5% to 0.25%. Similarly,

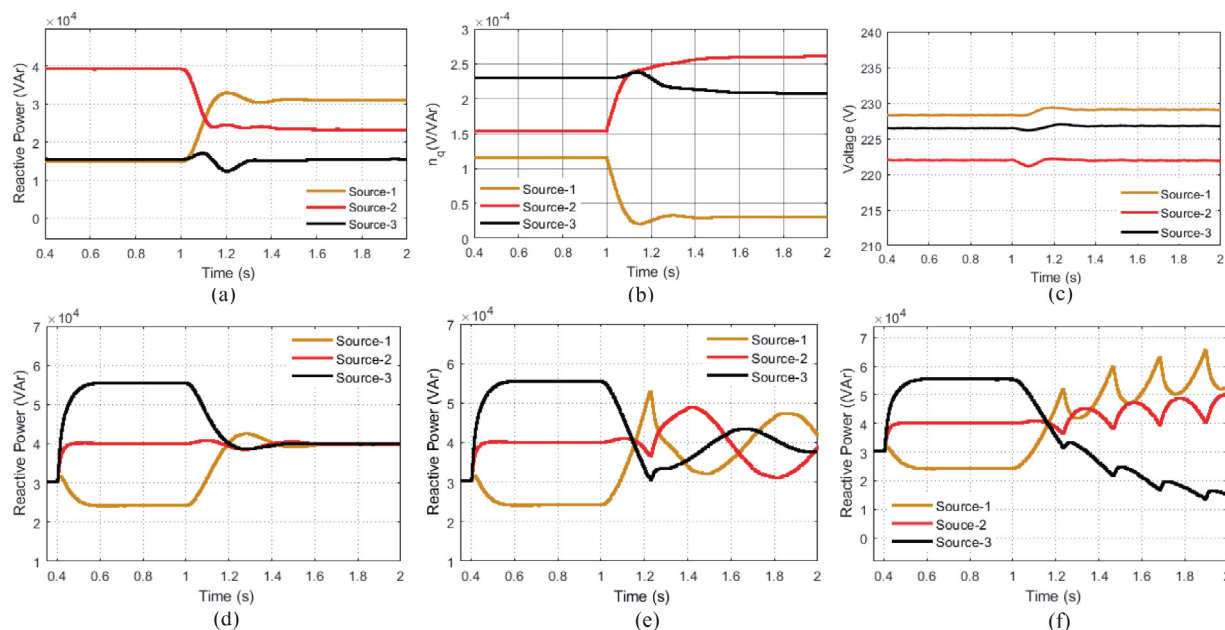


Fig. 12. Response of ac microgrid for sources with unequal capacities. (a) Waveforms of reactive power supplied by source-1, source-2 and source-3. (b) Waveform of $E - Q$ droop gains, n_{q1} , n_{q2} and n_{q3} and (c) Waveforms of voltages of source-1, source-2 and source-3. Response of ac microgrid for different values of time delays. Waveforms of reactive power supplied by source-1, source-2 and source-3 for a time delay of (d) 10 ms (e) 100 ms and (f) 500 ms.

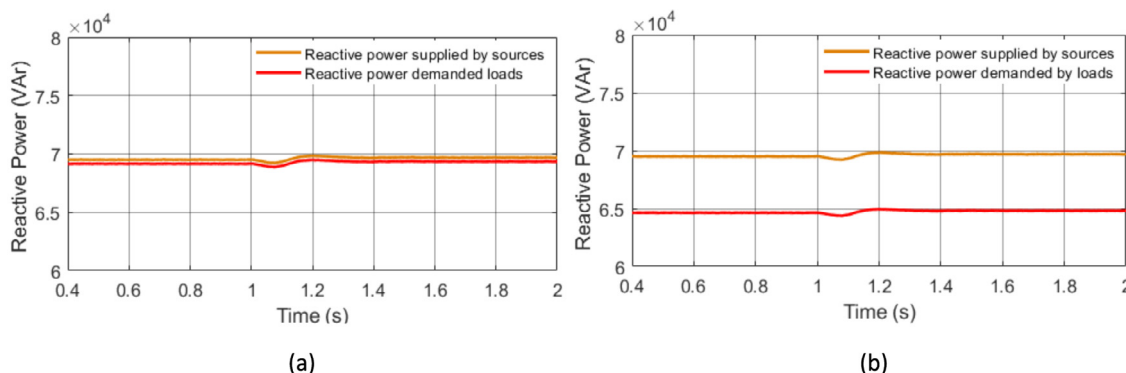


Fig. 13. Response of ac microgrid for sources with unequal capacities. (a) Waveforms of total reactive power supplied by the source-1, source-2, source-3 and total reactive power demanded by the loads using PRPS controller. (b) Waveforms of total reactive power supplied by the source-1, source-2, source-3 and total reactive power demanded by the loads using the controller suggested in [Shafiee et al. \(2014\)](#).

the in case of $R - C$ load, the error in reactive power-sharing is reduced from 27.5% to 0.75%. This validates the efficacy of the proposed controller. The effect of communication delay on the proportional controller is studied using the root loci plot. The delay margin of the proposed controller is observed to be 100 ms. The proposed controller requires only information of the reactive powers supplied by the sources for its implementation. This leads to the requirement of a low bandwidth communication channel which reduces the cost of the system. The low value of reactive power sharing errors and voltage regulation validates the viability of the proposed distributed secondary controller.

CRedit authorship contribution statement

Shirazul Islam: Conceptualization, Methodology, Software, Writing – original draft. **Atif Iqbal:** Supervision, Reviewing. **Souradip De:** Data curation, Investigation, Visualization, Software, Validation. **Farhad Ilahi Bakhsh:** Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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