Decentralised inverter control for improved reactive power sharing and voltage profile in a microgrid

Dharmendra Kumar Dheer1 | Yusuf Gupta2 | Suryanarayana Doolla2

1 Department of Electrical Engineering, National Institute of Technology Pama, Pama, India
2 Department of Energy Science and Engineering, Indian Institute of Technology Bombay, Mumbai, India

Abstract
This paper enhances a self-adjusting droop control strategy further to achieve an improved voltage profile in a microgrid along with proportional reactive power sharing amongst its sources. The proposed enhancement consists of an additional term in the “self-adjusting” nominal voltage. The proposed strategy is entirely decentralised and does not require information about the feeder impedance or the network topology. The proposed technique is robust and found to improve the voltage profile and the reactive power sharing for radial, meshed as well as reconfigured microgrid networks. Simulation studies have been performed on two test microgrids to assess and compare the performance of the proposed strategy. Experimental validation to confirm further the viability of the proposed strategy for several topological structures of the microgrid is done on a laboratory-scale microgrid.

1 | INTRODUCTION

Electric grid architecture is moving from being a centralised structure to a decentralised structure primarily due to penetration of distributed generation. The integration of distributed energy resources into the conventional power system has brought forward the concept of “microgrid” which can operate either in grid-connected mode or as an island. In the islanded mode of operation, the droop control technique is applied to the sources to achieve proportional power sharing [1]. It is well known that conventional droop helps in achieving proportional active power sharing among the sources [2, 3]. However, proportional reactive power sharing among the sources using droop control is far from ideal. The primary reason for the unequal reactive power sharing ($Q_{sh}$) is unequal feeder impedances, presence of local loads and random placement and sizes of loads amongst others. Unequal $Q_{sh}$ among the sources may lead to overloading of the sources and circulating current amongst them. These issues can be minimised by improving/achieving the proportional $Q_{sh}$ amongst the sources.

Various control strategies to achieve power sharing among the sources are reviewed in [3]. These control strategies can be broadly classified into droop control based techniques [4–15] and virtual impedance-based techniques [16–31]. For the conventional $Q - V$ droop technique, improved $Q_{sh}$ can be achieved by increasing the $Q - V$ droop coefficient ($n_q$). However, the increased value of $n_q$ causes a significant deviation in voltage, which is undesirable. An alternative approach can be to use the value of $Q - V$ droop coefficient ($n_q$) differently, even for the same rating of the sources [4–6] by adaptively changing their values. In [4], all the sources independently calculate and apply the $n_q$ adaptively to improve the $Q$-sharing. In [5], a sparse-communication-based technique among the neighbouring sources has been applied, which tunes the $n_q$, which in turn improves the $Q$-sharing. The technique is further modified in [6] by adaptively changing the value of $n_q$ to improve the $Q$-sharing among the sources.

A bidirectional communication-based control strategy with an adaptive adjustment of $n_q$ is proposed in [7] to improve the $Q_{sh}$. A $Q - V$ droop is proposed in [8] to improve the $Q_{sh}$. The proposed method improves $Q_{sh}$; however, it is affected by the $V$ restoration operation, which was later addressed in [9]. In [10], authors have proposed a real power injection-based disturbance to estimate the error in reactive power sharing. An integral term has been further added in the conventional $Q - V$ droop to eliminate the error in the $Q$-sharing during the transient period. The proposed correction in $Q - V$ droop modifies the $n_q$ to cancel out the effect of impedance mismatch and improve the reactive power sharing among the sources. The error in the proportional sharing of reactive power among the sources has
been analysed in [11] by performing sensitivity analysis on a small-signal model of the microgrid. Further, a distributed optimal control strategy has been proposed in which Kalman filter-based estimator and regulator have been employed to reduce the error in the sharing of reactive power among the sources. A self-adjusting \( Q - V \) droop technique is proposed in [12], and an appreciative improvement in \( Q_{sh} \) is achieved. However, the proposed method suffers from the voltage deviation issue, and the overall voltage of the network drops to a noticeable range. The drop in the magnitude of the voltage can be mitigated by implementing a correction using a secondary controller.

A two layer based control strategy has been proposed in [13] to improve the proportional reactive sharing among the sources in the islanded microgrid in which the bottom layer deals with the electrical network while the top layer concerns a communication-based network composed of agents. The agents exchange information with their neighbours to improve the reactive power sharing. In [14], separate energy server units and energy routers have been proposed to achieve proportional active and reactive power sharing among the sources separately. This scheme is costlier in comparison to other schemes due to an increased number of energy server units. A decentralised control scheme has been proposed in [15] to improve the reactive power sharing among the sources and to restore the system frequency to its nominal value. An integral controller based on the difference in the average active power output and instantaneous active power output has been added in the conventional \( Q - V \) droop to reduce the error in the reactive power sharing among the sources. However, the proposed modification is functional only under the transient condition.

Another well-known method for improving \( Q_{sh} \) is to insert either fixed or adaptively varying virtual impedance (\( Z_v \)). \( Z_v \) is designed so as to almost equalise the unequal feeder impedances and also to make the network inductive in nature. However, improper design of \( Z_v \) affects voltage quality and may degrade the \( Q_{sh} \). \( Z_v \) based control technique have been implemented in two ways: (i) without using communication [16–24] and (ii) by utilising communication [25–31]. A feeder impedance equalisation method using \( Z_v \) has been proposed in [17] to improve the \( Q_{sh} \). However, in this method, information of feeder parameter is required. A correction in the voltage droop is proposed using adaptive virtual capacitance in [18]. However, the tuning of the virtual capacitance under varying network topology is difficult, and hence, the proposed technique may not work satisfactorily in the reconfigured/meshed network.

The design of \( Z_v \) affects the power sharing, the transient response, voltage quality as well as the stability of the network. Hence, a trade-off needs to be achieved while designing \( Z_v \). The design of \( Z_v \) is more challenging when the loads and the network condition keeps on changing. Moreover, improper design of \( Z_v \) may result in poorer voltage quality, transient response, violation of power flow constraints, and sometimes it may also lead to instability. Considering these factors, authors in [21] have optimised a range for \( Z_v \) for improved \( Q \)-sharing among the sources under varying load condition. An alternative approach to design \( Z_v \) considering damping, node voltage constraint and \( P/Q \) decoupling information is presented in [22]. It is found that for the networks having significant differences in feeder impedances, obtaining the optimal value of \( Z_v \) is difficult. Another approach to obtain an optimal value of \( Z_v \) for the meshed network using genetic algorithm has been proposed in [23]. The found method is network-specific, and it requires offline calculations when the network topology changes. Communication-based approaches for \( Z_v \) design can give better \( Q_{sh} \), but these techniques are found to be quite expensive and computationally intensive [27–30].

It is desired that the control scheme should work irrespective of the network structure (radial, meshed, reconfigured). A change in network topology causes a change in impedance as seen by the sources, which may also cause an increase in the coupling between the real and reactive power. This coupling may lead to poor performance in power sharing. Authors in [20] have implemented \( Z_v \) based modification, which is found to be satisfactory for the reconfigured/meshed networks. However, the proposed technique requires a communication link to send the reference bus data to the local controllers. A method to improve the \( Q_{sh} \) for reconfigured/meshed network without any communication channel is not found in the literature so far.

Control strategies to improve the \( Q_{sh} \) based on either droop control or \( Z_v \) based control cause voltage deviations from the nominal values. The deviation should be restored or minimised for the effective operation of the microgrid. It can either be minimised by modifying the existing droop techniques or by implementing the secondary controller. Frequency and voltage restoration technique using communication is proposed in [32–35]. A consensus-based distributed voltage control is proposed in [36], which keeps the output voltage in the permissible range of operation. However, the proposed technique requires distributed communication among the sources. The self-adjusting \( Q - V \) droop technique proposed by us in our previous work [12] also suffers from the voltage deviation issue. To the best of the authors’ knowledge, voltage profile improvement in addition to improved \( Q_{sh} \) without the use of communication network is not found in the literature so far.

This paper presents a robust droop control strategy (RDCS) for improved voltage profile in addition to proportional \( Q_{sh} \) without the use of communication. It is to be noted that the proposed control modification is based on the authors’ previous work presented in [12]. In this work:

- An RDCS is proposed by modifying the self-adjusting \( Q - V \) droop technique to improve the voltage profile in addition to improving \( Q_{sh} \) in a droop based microgrid.
- The proposed RDCS is tested for different microgrid topologies, including network reconfiguration and mesh formation.

The significance of the work are as follows. The proposed technique is able to maintain the voltage of the network closer to 1.0 pu without sacrificing the improvement achieved in \( Q_{sh} \) in [12]. Moreover, application of the proposed RDCS alleviates the task of voltage regulation which is usually taken care by a secondary controller.

The paper is organised as follows: RDCS is presented in Section 2. Simulation studies are presented in Section 3.
Selection of control parameter, eigenvalue analysis and mathematical approach to obtain the effect of the control parameter on $Q_{th}$ is presented in Section 4. Section 5 contains the experimental validation followed by conclusion in Section 6.

2 ROBUST DROOP CONTROL STRATEGY

In this section, the proposed RDCS has been presented. Conventional $P - \omega$ droop control ($\omega = \omega_a - m_p P$) has been applied to the sources for active power sharing. The voltage control has been implemented in the dq reference frame wherein the d-axis reference voltage is completely aligned to the d-axis output voltage ($V_d$) of the inverter and the q-axis reference voltage is set to zero. The conventional $Q - V$ droop is given as follows:

$$V = V_a - n_q Q. \quad (1)$$

The voltage at a node based on the self-adjusting $Q - V$ droop proposed by authors in the previous work [12] is given by:

$$V = \left( \frac{\beta + V_{pu}}{\beta + \omega_{pu}} \right) V_a - n_q Q. \quad (2)$$

where $\beta$ is a tuning parameter, $V_{pu}$ and $\omega_{pu}$ are per unit output voltage and system frequency respectively. It is found that the application of the above technique results in a noticeable drop in voltage in the network. In the proposed RDCS, the nominal voltage $V_a$ adjusts automatically in such a way that the voltage profile of the network and the $Q_{th}$ among the sources improves simultaneously. To minimise the voltage deviation, following RDCS is proposed.

$$V = \left( \frac{\beta + V_{pu} + \beta_{add}}{\beta + \omega_{pu}} \right) V_a - n_q Q. \quad (3)$$

The control parameter $\beta_{add}$ in (3) plays a significant role in the voltage improvement process. The selection of $\beta_{add}$ is critical (as will be explained later in Section 4).

Voltage deviation of the DG connected at the $r^{th}$ node, $\Delta V_r$ ($V_r - V_i$) has been determined for droop laws expressed in (1)–(3). Voltage deviation in the case of (1) is given by:

$$\Delta V_i = n_q L_i. \quad (4)$$

Voltage deviation in case of (2) is given by:

$$\Delta V_r = \left( \frac{\omega_{pu}}{\beta} \right) n_q L_i - \left( \frac{1 - \omega_{pu}}{\beta} \right) V_i. \quad (5)$$

Since $\omega_{pu} \approx 1$, the second term on the right hand side of (5) can be neglected, and $\Delta V_r$ simplifies to $n_q L_i \left( 1 + \frac{1}{\beta} \right)$. Hence, a positive value of $\beta$ causes the $\Delta V_r$ to increase further as compared to (4). Furthermore, the introduction of $\beta_{add}$ in the proposed RDCS as expressed in (3) modifies the expression of $\Delta V_i$ as shown below:

$$\Delta V_i \approx n_q L_i \left( 1 + \frac{1}{\beta} \right) - \frac{\beta_{add}}{\beta} V_i. \quad (6)$$

As seen from the above equation, $\Delta V_i$ decreases for a positive value of $\beta_{add}$. This explains the reduction in the voltage deviation by the application of the RDCS.

3 SIMULATION STUDIES

Time-domain simulation is performed in MATLAB/Simulink to validate the claim of improved reactive power sharing among the sources in addition to voltage improvement in the network. The performance of the conventional $Q - V$ droop, self-adjusting $Q - V$ droop and the RDCS is compared by simulating the test systems shown in Figures 1 and 4. All the simulation studies are performed in a similar fashion in which initially all the sources are operating in conventional droop technique, at $t = 10$ s the sources are switched to the self-adjusting droop control technique and $t = 20$ s the sources are switched to the proposed RDCS.

3.1 Microgrid test system 1

The performance of the RDCS is assessed and compared with the previous work in case of common load (CL) and for the case of common plus local load (LL). Microgrid test system 1 (MG1) shown in Figure 1 is adapted from [12]. The line and load data are given in Table 1. The value of $\beta$ is set to 0.2 for both MG1 and MG2 for all the cases. It is also assumed that all the DGs are of the same rating. The inverter parameters for MG1 are: $L_f = 3$ mH, $C_f = 50$ μF, $\omega_a = 314.16 \text{ rad/s}$, $V_{dc} = 450 \text{ V}$ and $V_e = 155.6 \text{ V}$. The controller parameters for MG1 are: $m_p = 5e - 5 \text{ rad/(W s)}$, $n_q = 5e - 4 \text{ V/VAr}$, $\omega_r = 6.28 \text{ rad/s}$,
3.1.1 | MG1: Case-1 (common load)

The common load is located at the ac bus. Active power ($P$), reactive power ($Q$) and $v_{odr}$ of the sources operating in conventional droop, self-adjusting $Q - V$ droop and proposed RDCS is shown in Figure 2 and is also tabulated in Table 2. The error in reactive power sharing for the $k^{th}$ source, $Q_{err-k}$ can be defined as follows:

$$Q_{err-k} = \frac{Q_k - Q_{exp}}{Q_{exp}} \times 100, \quad (7)$$

where $Q_{exp}$ is the expected share of reactive power desired from the $k^{th}$ source. For example, for three equally rated sources, $Q_{exp1} = Q_{exp2} = Q_{exp3} = \frac{Q_{total}}{3}$; while for sources whose ratings are in the ratio of 1:1:2, the expression $2Q_{exp1} = Q_{exp2} = \frac{Q_{exp3} = Q_{total}}{2}$ holds. It can be seen that proportional active power sharing among the sources are achieved due to $P - \omega$ droop. The $Q_{sh}$ among the sources with conventional droop is not proportional to their ratings. The $Q_{sh}$ is improved in case of the self-adjusting $Q - V$ droop technique [12]. However, the voltage deviations in this method are higher in comparison to the conventional $Q - V$ droop. It can be seen from Table 2 that the $Q_{sh}$ among the sources in the case of self-adjusting $Q - V$ droop technique and RDCS are similar. The minimum value of DG output voltage ($v_{odr}$) in the case of self-adjusting $Q - V$ droop technique is 0.968 pu which is improved to 0.986 pu in case of the proposed RDCS. The additional term in the voltage deviation ($\frac{\beta_{add}}{\beta} V_n$) in (6) in comparison to (5) improves the minimum DG output voltage in the network from 0.968 pu to 0.986 pu. It is to be noted that the loads considered for all the case studies are constant impedance loads. The power consumed by these loads is directly proportional to the square of the applied voltage. Therefore, as seen in Figure 2, the active power consumed by the loads drop significantly during the ‘B’ period as compared to the ‘A’ and the ‘C’ period because of a drop in the voltage magnitude.

3.1.2 | MG1: Case-2 (common plus local load)

The local load is connected at the output of DG1 while keeping the common load intact into the network. Active power ($P$), reactive power ($Q$) and $v_{odr}$ of the sources operating in conventional droop, self-adjusting $Q - V$ droop and proposed RDCS is shown in Figure 3 and is also tabulated in Table 3. It can be seen that the $Q_{sh}$ among the sources for the conventional $Q - V$ droop technique is not proportional, which
Table 3: MG1: Case-2 (common plus local load)

| Droop type | $P_{1-3}$ (kW) | $Q_{1-3}$ (kVar) | $Q_{exp}$ (kVar) | $Q_{err(1-3)}$ (%) | $vodr$ (1-3) |
|------------|---------------|-----------------|-----------------|-------------------|------------|
| Conventional droop | 3.40 | 4.78, 0.86, 1.68 | 185, | −49, 0.984, 0.997 |
| Self-adjusting droop | 3.25 | 2.35, 1.44, 1.60 | 47, | −10, 0.958, 0.975 |
| RDCS | 3.35 | 2.42, 1.48, 1.65 | 46.7, | −10.3, 0.976, 0.994 |

Figure 4: Test system MG2

gets improved due to the self-adjusting $Q - V$ droop. However, the voltage deviation is high in this method. It can be seen that the minimum value of DG output voltage ($vodr$) in the case of self-adjusting $Q - V$ droop technique is 0.958 pu which is improved to 0.976 pu in case of the proposed RDCS.

3.2 | Microgrid test system 2

The network Microgrid test system 2 (MG2) as shown in Figure 4 is used to assess the performance under different network topologies (radial, reconfigured and meshed network). MG2 is adapted from [37] to test the performance of all the three methods in case of the reconfigured and meshed network. The line and load data of MG2 are as shown in Table 4. The switch position and topological structure of the microgrid is shown in Table 5. The inverter parameters for MG2 are: $L_f = 1.8$ mH, $C_f = 65 \mu F$, $\omega_n = 314.16$ rad/s, $V_{dc} = 1000$ V and $V_n = 380$ V. The controller parameters for MG2 are: $m_p = 1e-4$ rad/(W s), $m_q = 1.3e-3$ V/VAr, $\omega_l = 6.28$ rad/s, $\beta = 0.2$ and $\beta_{add} = 0.001$. An upper and a lower limit is set for both the d-axis output current ($i_{od}$) and the q-axis output current ($i_{oq}$) for all the DGs. It is very common to set these current limits to 1.5 times of their rated values. The rating and current limits are: $i_{od} = 40$ A (corresponding to 10.0 kW, $i_{od_{rated}} = 26.3$ A), $i_{oq} = 20$ A (corresponding to 5 kVAr, $i_{oq_{rated}} = 13.2$ A).

3.2.1 | MG2: Case-1 (radial network)

For the radial structure of the MG2 shown in Figure 4, the switch $S_1$ is closed and switch $S_2$ is kept open. Active power ($P$), reactive power ($Q$) and $vodr$, where $A =$ conventional droop, $B =$ self-adjusting droop and $C =$ RDCS is shown in Figure 5 and is also tabulated in Table 6. It can be seen that the $Q_{sh}$ among the sources for the con-

Table 4: MG2 network data

| Line no. | Impedance ($\Omega$) | R/X | Node no. | Load (kVA) |
|----------|-----------------|-----|----------|------------|
| L1       | 0.10 + j 0.08   | 1.25| 1        | 2.0 + j 0.5 |
| L2       | 0.20 + j 0.35   | 0.57| 2        | 1.0 + j 0.3 |
| L3       | 0.15 + j 0.19   | 0.79| 3        | 5.0 + j 3.0 |
| L4       | 0.20 + j 0.10   | 2.00| 4        | 1.5 + j 1.0 |
| L5       | 0.18 + j 0.25   | 0.72| 5        | 1.0 + j 0.1 |
| L6       | 0.15 + j 0.16   | 0.94| 6        | 5.0 + j 1.0 |

Table 5: Switch position and network topology

| Topology             | Switches          |
|----------------------|-------------------|
| Radial network       | $S_1$: Close, $S_2$: Open |
| Reconfigured network | $S_1$: Open, $S_2$: Close |
| Meshed network       | $S_1$: Close, $S_2$: Close |

Table 6: MG2: Case-1 (radial network)

| Droop type | $P_{1-3}$ (kW) | $Q_{1-3}$ (kVar) | $Q_{exp}$ (kVar) | $Q_{err(1-3)}$ (%) | $vodr$ (1-3) |
|------------|---------------|-----------------|-----------------|-------------------|------------|
| Conventional droop | 5.15 | 1.10, 2.40, 2.01 | −45.3, 19.4 | 1.001, 0.996 |
| Self-adjusting droop | 5.06 | 1.68, 2.05, 1.96 | −14.4, 4.44 | 0.994, 0.986 |
| RDCS       | 5.10 | 1.72, 2.08, 1.99 | −13.7, 4.3 | 1.001, 0.992 |

FIGURE 5: MG2 radial network: $P$, $Q$ and $vodr$, where $A =$ conventional droop, $B =$ self-adjusting droop and $C =$ RDCS.
3.2.2 | MG2: Case-2 (reconfigured network)

For the reconfigured structure of the MG2 shown in Figure 4, the switch $S_1$ is kept open and switch $S_2$ is closed. Active power ($P_i$), reactive power ($Q_i$) and $v_{odr}$ of the sources operating in conventional droop, self-adjusting $Q - V$ droop and proposed RDCS is shown in Figure 6 and is also tabulated in Table 7. It can be seen that the $Q_{sh}$ among the sources for the conventional droop is not proportional, which is further improved by implementing the self-adjusting $Q - V$ droop technique. However, the voltage deviation is high in the case of self-adjusting $Q - V$ droop as compared to the conventional droop. It can be seen that the minimum value of DG output voltage ($v_{odr}$) in the case of self-adjusting $Q - V$ droop technique is 0.984 pu which is improved to 0.990 pu by the application of the RDCS.

3.2.3 | MG2: Case-3 (meshed network)

For the meshed structure of the MG2, both the switches $S_1$ and $S_2$ are kept closed. Active power ($P_i$), reactive power ($Q_i$) and $v_{odr}$ of the sources operating in conventional droop, self-adjusting $Q - V$ droop and proposed RDCS is shown in Figure 7 and is also tabulated in Table 8. It can be seen that the $Q_{sh}$ among the sources for the conventional droop is disproportional, which is further improved by implementing the self-adjusting $Q - V$ droop technique. However, the voltage deviation is high in the case of self-adjusting $Q - V$ droop as compared to the conventional droop. It can be seen that the minimum value of DG output voltage in the case of self-adjusting $Q - V$ droop technique is 0.984 pu which is improved to 0.990 pu by the use of RDCS.
TABLE 9 Virtual impedance implementation: $R_v = \text{constant}, X_v = \text{variable}$

| Virtual impedance (Ω) | $P_{1-3}$ (kW) | $Q_{1-3}$ (kVAR) | $Q_{exp}$ (kVAR) | $Q_{err(1-3)}$ (%) | $\nu_{vd(1-3)}$ (pu) |
|------------------------|----------------|------------------|-----------------|------------------|---------------------|
| $R_v = 0, X_v = 0.1$   | 3.35           | 3.66, 1.17, 0.12  | 1.65            | 121.8, −29.1, −92.7 | 0.988, 0.996, 1.000 |
| $R_v = 0, X_v = 0.2$   | 3.31           | 3.12, 1.31, 0.49  | 1.64            | 90.2, −20.1, −70.1 | 0.990, 0.996, 0.998 |
| $R_v = 0, X_v = 0.3$   | 3.28           | 2.78, 1.37, 0.71  | 1.62            | 71.6, −15.4, −56.2 | 0.991, 0.995, 0.998 |
| $R_v = 0, X_v = 0.4$   | 3.24           | 2.55, 1.40, 0.85  | 1.6             | 59.4, −12.5, −46.9 | 0.991, 0.996, 0.997 |
| $R_v = 0, X_v = 0.5$   | 3.21           | 2.39, 1.42, 0.95  | 1.59            | 50.6, −10.5, −40.1 | 0.992, 0.996, 0.997 |
| $R_v = 0, X_v = 0.6$   | 3.18           | 2.26, 1.43, 1.02  | 1.57            | 44.0, −8.9, −35.0  | 0.992, 0.995, 0.997 |
| $R_v = 0, X_v = 0.7$   | 3.15           | 2.16, 1.43, 1.08  | 1.56            | 38.9, −8.0, −30.9  | 0.993, 0.995, 0.996 |
| $R_v = 0, X_v = 0.8$   | 3.12           | 2.07, 1.43, 1.12  | 1.54            | 34.4, −7.1, −27.3  | 0.993, 0.995, 0.996 |
| $R_v = 0, X_v = 0.9$   | 3.09           | 2.0, 1.43, 1.14   | 1.52             | 31.3, −6.1, −25.1  | 0.993, 0.995, 0.996 |
| $R_v = 0, X_v = 1.0$   | 3.05           | 1.94, 1.42, 1.16  | 1.51             | 28.7, −5.7, −23.0  | 0.993, 0.995, 0.996 |

TABLE 10 Virtual impedance implementation: $R_v = \text{constant}, X_v = \text{variable}$

| Virtual impedance (Ω) | $P_{1-3}$ (kW) | $Q_{1-3}$ (kVAR) | $Q_{exp}$ (kVAR) | $Q_{err(1-3)}$ (%) | $\nu_{vd(1-3)}$ (pu) |
|------------------------|----------------|------------------|-----------------|------------------|---------------------|
| $R_v = 0.1, X_v = 0.0$ | 3.35           | 4.68, 0.85, −0.59 | 1.65            | 184.2, −48.4, −135.8 | 0.984, 0.997, 1.002 |
| $R_v = 0.1, X_v = 0.5$ | 3.16           | 2.35, 1.40, 0.94  | 1.56             | 50.3, −10.4, −39.9  | 0.992, 0.995, 0.997 |
| $R_v = 0.1, X_v = 1.0$ | 3.01           | 1.91, 1.40, 1.15  | 1.49             | 28.5, −5.8, −22.6   | 0.994, 0.996, 0.996 |

3.3 Comparison of RDCS to virtual impedance technique

The performance of the RDCS is compared with the virtual impedance technique for common plus local load case. The local load is connected near the $DG_1$ as shown in Figure 1. Four case studies have been performed by implementing the virtual impedance technique. The $P$, $Q$ and $\nu_{vd}$ values have been obtained for the following cases:

- Case-I: Value of $R_v$ kept constant (0 Ω) and the value of $X_v$ varies from 0.1 to 1.0 Ω in the steps of 0.1 Ω (results are presented in Table 9).
- Case-II: Value of $R_v$ kept constant (0.1 Ω) and the value of $X_v$ varies from 0.0 to 1.0 Ω in the steps of 0.5 Ω (results are presented in Table 10).
- Case-III: Value of $X_v$ kept constant (0.5 Ω) and the value of $R_v$ varies from 0.1 to 0.5 Ω in the steps of 0.1 Ω (results are presented in Table 11).
- Case-IV: Value of $X_v$ kept constant (0.5 Ω) and the value of $R_v$ varies from −0.1 to −0.5 Ω in the steps of 0.1 Ω (results are presented in Table 12).

It can be seen from Tables 9 and 10 that for the fixed value of $R_v$ (case-I: $R_v = 0$ and case-II: $R_v = 0.1$) the error in $Q_{sh}$ decreases if the value of $X_v$ is increased. However, $P$ output and the average value of the $Q$ output of the sources decreases, which is a drawback of the virtual impedance control. The nominal value of $P$ decreases from 3.40 to 3.05 kW and the average value of $Q$ also decreases from 1.68 to 1.51 kVAR for the value of $R_v = 0$ and $X_v = 1$ (refer to Table 9). For the $R_v = 0.1$ and $X_v = 1$, the nominal value of $P$ decreases from 3.40 to 3.01 kW and the average value of $Q$ also decreases from 1.68 to 1.49 kVAR (refer to Table 10).

Whereas $P$ and average $Q$ for RDCS is 3.35 kW and 1.65 kVAR, respectively which is better in comparison to the virtual impedance technique. The error in reactive power sharing is less in the case of RDCS in comparison to the lower value of $X_v$ in virtual impedance technique. However, for the higher values of $X_v$, the error in reactive power sharing in virtual impedance technique is less in comparison to the proposed RDCS.

Refer to Table 11, increasing value of $R_v$ by keeping $X_v$ constant does not bring significant change in the $Q_{err}$. However, increasing value of $R_v$ by keeping $X_v$ constant results in noticeable decrement in $P$ and average value of $Q$ output of the sources which is not desirable.

Table 12 presents the effect of negative value of $R_v$ on $Q_{sh}$ among the sources. The value of $X_v$ is kept constant (0.5 Ω) and the value of $R_v$ is decreased in the steps of 0.1 Ω from −0.1 to −0.5 Ω. Decreasing the value of $R_v$ increases the $P$ and average value of $Q$ output of the sources. It has minimal effect on $Q_{err}$. However, for the lower values of $R_v$, oscillation in power output is observed.

The results obtained using the virtual impedance technique have been compared with the results obtained using the RDCS. It has been observed that for the higher values of $X_v$, $Q_{err}$ is lesser in comparison to the RDCS. However, the total sum of active power output and reactive power output of the sources...
TABLE 11 Virtual impedance implementation: $R_v = \text{variable}, X_v = \text{constant}$

| Virtual impedance ($\Omega$) | $P_{1-3}$ (kW) | $Q_{1-3}$ (kVAR) | $Q_{ep}$ (kVAR) | $Q_{err(1-3)}$ (%) | $\nu_{add(1-3)}$ (pu) |
|-----------------------------|----------------|-----------------|----------------|-------------------|---------------------|
| $R_v = 0.1, X_v = 0.5$     | 3.16           | 2.35, 1.40, 0.94| 1.56           | 50.3, −10.4, −39.9| 0.992, 0.995, 0.997 |
| $R_v = 0.2, X_v = 0.5$     | 3.1            | 2.30, 1.37, 0.92| 1.53           | 50.3, −10.5, −39.5| 0.992, 0.995, 0.997 |
| $R_v = 0.3, X_v = 0.5$     | 3.06           | 2.26, 1.35, 0.91| 1.51           | 50.0, −10.4, −39.6| 0.992, 0.995, 0.997 |
| $R_v = 0.4, X_v = 0.5$     | 3.0            | 2.22, 1.33, 0.90| 1.48           | 50.0, −10.3, −39.67| 0.992, 0.995, 0.997 |
| $R_v = 0.5, X_v = 0.5$     | 2.95           | 2.17, 1.31, 0.88| 1.45           | 49.3, −9.9, −39.5  | 0.993, 0.995, 0.997 |

TABLE 12 Virtual impedance implementation: $R_v = \text{variable}, X_v = \text{constant}$

| Virtual impedance ($\Omega$) | $P_{1-3}$ (kW) | $Q_{1-3}$ (kVAR) | $Q_{ep}$ (kVAR) | $Q_{err(1-3)}$ (%) | $\nu_{add(1-3)}$ (pu) |
|-----------------------------|----------------|-----------------|----------------|-------------------|---------------------|
| $R_v = −0.1, X_v = 0.5$    | 3.27           | 2.42, 1.45, 0.97| 1.61           | 50.0, −10.1, −39.9| 0.991, 0.995, 0.997 |
| $R_v = −0.2, X_v = 0.5$    | 3.35           | 2.47, 1.48, 0.98| 1.64           | 50.3, −9.9, −40.4  | 0.992, 0.995, 0.997 |
| $R_v = −0.3, X_v = 0.5$    | Oscillatory    | Oscillatory     | −              | −                 | Oscillatory         |
| $R_v = −0.4, X_v = 0.5$    | Oscillatory    | Oscillatory     | −              | −                 | Oscillatory         |
| $R_v = −0.5, X_v = 0.5$    | Oscillatory    | Oscillatory     | −              | −                 | Oscillatory         |

decreases in comparison to RDCS, which is not at all desirable. Apart from the drawback of $P/Q$ reduction, implementation of virtual impedance technique also needs feeder current information which is not usually accessible. The RDCS does not require any feeder current information or communication among the sources.

4 CONTROL PARAMETERS $\beta$ AND $\beta_{add}$ SELECTION, EIGENVALUE ANALYSIS AND EFFECT OF $\beta_{add}$ ON $Q_{sh}$

In this section, the process followed in selecting $\beta$ and $\beta_{add}$ is presented. It is important to study the effect of $\beta_{add}$ on small signal stability margin, and on the $Q_{sh}$. Eigenvalue analysis is performed to study the same.

4.1 Selection of control parameters ($\beta$ and $\beta_{add}$)

The selection of the control parameters $\beta$ and $\beta_{add}$ is critical to the performance of the system. To obtain a suitable value of $\beta$ for system-1, $\beta$ has been varied starting from 100 and is decreased until 0.05 as shown in Table 13. The values related to the $Q$ sharing, voltage magnitudes, and the dominant poles determined using eigenvalue analysis have been listed in Table 13.

It can be observed that as the value of $\beta$ reduces, the magnitude of $Q_{err(1-3)}$ decreases, indicating an improved $Q$ sharing. However, for the value of $\beta$ below 0.1 causes an oscillatory behaviour in power output. For $\beta$ of 0.05, the system eigenvalues move towards the unstable region. Hence, a balance has to be achieved between the achievable $Q$ sharing and the system stability. Hence, a value of 0.2 has been chosen for $\beta$ for system-1.

The same study has been carried out for system-2 considering all the three topological structures (radial, reconfigured and meshed). Results for the radial system is shown in Table 14 and the most appropriate value of $\beta$ is found to be 0.20.

Once the value of $\beta$ gets fixed, the value of $\beta_{add}$ needs to be determined. To obtain a suitable value of $\beta_{add}$, same steps have been carried out as performed for choosing $\beta$. Several case studies have been performed for system-1 with common load case and with common plus local load case. The results for variation of $\beta_{add}$ for common plus local load case have been included in Table 15. As seen from the dominant eigenvalues listed in Table 15, $\beta_{add}$ has minimal effect on the stability of the system as well as on the $Q$ sharing performance. $\beta_{add}$ should be selected such that the value of $\nu_{add}$ reaches nearer to 1 pu. Besides, maintaining voltage across the network nearer to 1 pu also facilitates synchronisation with other microgrids or with the grid without resorting to the secondary controller-based voltage restoration. It can be observed that for $\beta_{add}$ of 0.004, the voltages are most nearer to 1 pu. Hence, a value of 0.004 is set for $\beta_{add}$ for system-1.

Similar case studies have been performed for setting the value of $\beta_{add}$ for system-2 considering several topological structure (radial, reconfigured and meshed). The results for the system-2 for radial network are as shown in Table 16. A value of 0.001 is found to be appropriate for system-2.

4.2 Eigenvalue analysis

Eigenvalue plots and eigenvalue traces of the microgrid utilising the RDCS is obtained by varying $\beta_{add}$ for all the case studies. The eigenvalue plot of the MG1 (case-2) is as shown in
Figure 8. The eigenvalues can be classified into three groups: low-frequency, medium-frequency and high-frequency modes. Low-frequency modes correspond to the power controller loop of the voltage source inverter [38]. The droop controller is associated with the power controller loop, and hence, the low-frequency modes are sensitive to the parameters related to the droop controller. Eigenvalue trace is obtained by varying the $\beta$ add as shown in Figure 9. $\beta$ add is varied from 0.0 to 0.1 in the step of 0.0001. Little variation (towards imaginary axis) in the sensitive eigenvalues corresponding to the modes associated to DG-1 and DG-2 ($\lambda_{12}$) and DG-2 and DG-3 ($\lambda_{23}$) is observed. From the eigenvalue trace, it is found that the parameter $\beta$ add has minimal effect on the stability of the network.
4.3 | Effect of $\beta_{\text{add}}$ on $Q_{\text{sh}}$: Mathematical approach

In this section, the effect of $\beta_{\text{add}}$ on the improvement in $Q_{\text{sh}}$ is discussed. The $Q_{\text{sh}}$ obtained using the proposed RDSCS is compared with the $Q_{\text{sh}}$ obtained using the self-adjusting $Q - \sqrt{3}$ droop technique. The expression of $i_{\text{q1}} - i_{\text{q2}}$ as shown below roughly corresponds to the circulating current among the two sources. The following is assumed in this study:

- The islanded microgrid consists of two equally rated sources ($n_{q1} = n_{q2} = n_q$ and $m_{pl} = m_{p2} = m_p$).
- The difference in the $q$-axis component of the output currents ($i_{\text{q1}} - i_{\text{q2}}$) is analogous to the difference in Q-sharing between the $DG_1$ and $DG_2$. 
- The $d$-axis component of the current of the $DG_1$ and $DG_2$ are approximately equal: $i_{\text{d1}} \approx i_{\text{d2}} = i_{\text{d}}$.

The difference in the $q$-axis component of currents [12] is:

$$i_{\text{q1}} - i_{\text{q2}} \approx \frac{C}{A' + \frac{1.5c_{12}c_{32}c_{31}}{\beta V_0}} i_{\text{d}}$$  

(8)
FIGURE 8  MG1: Eigenvalue plot with proposed RDCS for case-2 (3)

FIGURE 9  MG1: Eigenvalue for low-frequency modes with $0 \leq \beta_{\text{add}} \leq 0.1$ in the step of 0.0001

where

$$C = 1.5n_q(r_{ad1} - r_{ad2})(X_1 - X_2) + (R_1 - R_2)^2 + (X_1 - X_2)^2$$

$$A' = 1.5n_q(r_{ad2}R_1 - r_{ad1}R_2) + X_2R_1 - X_1R_2$$

A similar exercise to obtain $i_{aq1} - i_{aq2}$ for the RDCS has been carried out. The difference in the q-axis component of currents obtained for the proposed RDCS equation is given as follows:

$$i_{aq1} - i_{aq2} \approx \frac{C}{A' + \frac{1.5n_q(r_{ad2}R_1 - r_{ad1}R_2) + X_2R_1 - X_1R_2}{(\beta + \beta_{\text{add}})V_n}}$$  \hspace{1cm} (9)

It can be seen from (8) and (9) that the denominator of the fractional term in the denominator is changed from $\beta V_n$ to $(\beta + \beta_{\text{add}})V_n$. However, rest all terms remain the same. It is observed that the value of $\beta_{\text{add}}$ is very small in comparison to the value of $\beta$. Hence, the value of $(\beta + \beta_{\text{add}}) \approx \beta$ and the effect of $\beta_{\text{add}}$ on $Q_{\text{sh}}$ is minimal in comparison to $Q_{\text{sh}}$ among the sources achieved in the self-adjusting $Q - V$ droop technique.

5  EXPERIMENTAL VALIDATION

The performance of the proposed RDCS is validated and compared with the conventional and the self-adjusting droop technique on a low-voltage laboratory prototype shown in Figure 10. The circuit diagram of the prototype is as shown in Figure 11. The inverters ($DG_1$, $DG_2$ and $DG_3$) are controlled using the Texas Instrument TMS320F28335 digital signal controller. The inverter and controller parameters are shown in Table 17. Line and load data are as shown in Table 18.

Experiments are performed for the cases including base case, reconfigured case and mesh formation in the network. For the base case, switches $S_1$, $S_3$ and $S_4$ are closed and $S_2$ is open. For the network reconfiguration, switches $S_1$, $S_2$ and $S_3$ are closed while $S_4$ is open. For the meshed network case, all four switches are closed. The value of $\beta$ and $\beta_{\text{add}}$ are chosen to be 0.4 and 0.02, respectively. The value of $\beta_{\text{add}}$ is chosen in such a way that the maximum voltage in the network becomes $\approx 1.0 \text{ pu}$. It is to be noted that the value of $m_p$ and $n_q$ are kept the same for all the cases.

5.1  Base case

Initially, all the DGs are operating with conventional $Q - V$ droop. At $t = 6 \text{ s}$, self-adjusting $Q - V$ droop technique is applied to all the DGs, and at $t = 17 \text{ s}$ the proposed RDCS is applied to all the DGs, respectively. The results for all the three droop techniques are shown in Table 19. $Q_{\text{err}}$ (in percentage) in the case of conventional droop is found to be $-106, 31$ and $75$ for DG-1, DG-2 and DG-3, respectively. The

| Table 17 | Inverter and controller parameters |
|---------|-----------------------------------|
| Parameter | Value | Controller parameter | Value |
| $L_f$ | 3 mH | $m_p$ | 2.5$\pi - 4 \text{ rad/(W s)}$ |
| $C_f$ | 50 $\mu F$ | $n_q$ | 1$\pi - 2 \text{ V/Var}$ |
| $f_s$ | 50 Hz | $\omega_s$ | 31.41 rad/s |
| $\omega_s$ | 314.16 rad/s | $\beta$ | 0.4 |
| $f_{sw}$ | 10 kHz | $\beta_{\text{add}}$ | 0.02 |

| Table 18 | Line and load data |
|---------|-------------------|
| Line | Impedance ($\Omega$) | R/X | Load | Power (VA) |
| L1 | 0.15 + j 0.314 | 0.47 | Load$_1$ | 360 + j 0 |
| L2 | 0.15 + j 0.628 | 0.24 | Load$_2$ | 625 + j 240 |
| L3 | 0.15 + j 0.314 | 0.47 | Load$_3$ | 625 + j 0 |
| L4 | 0.15 + j 0.314 | 0.47 | Load$_4$ | 270 + j 120 |
FIGURE 10  Microgrid with three DGs and loads

FIGURE 11  Three inverter microgrid for experimental validation

TABLE 19  Experimental results: Base case

| Droop type         | $P_{1-3}$ (W) | $Q_{1-3}$ (Var) | $Q_{exp}$ (Var) | $Q_{err(1-3)}$ (%) | $\eta_{adv(1-3)}$ (pu) |
|--------------------|---------------|----------------|----------------|--------------------|------------------------|
| Conventional drop  | 598           | −8, 181        | 139            | −106, 31           | 1.001, 0.970            |
| Self-adjusting     | 543           | 77, 138        | 124            | −38.8, 11          | 0.959, 0.922            |
| RDCS               | 586           | 86, 149        | 135            | −36, 10            | 0.998, 0.959            |

self-adjusting $Q-V$ droop reduces the percentage $Q_{err}$ (to $-38.8, 11$ and $27$ for DG-1, DG-2 and DG-3, respectively) but the overall voltage profile of the network deteriorates and the minimum value of DG output voltage in the network reaches to 0.910 pu. In the case of proposed RDCS, the percentage $Q_{err}$ ($-36, 10$ and $26$ for DG-1, DG-2 and DG-3, respectively) is similar to the self-adjusting droop but the overall voltage profile of the network improves and the minimum value of DG output voltage in the network becomes 0.947 pu as seen in Figure 12. The maximum value of DG output voltage in the case of self-adjusting droop is 0.959 pu which gets improved to 0.998 pu ($\approx 1.0$ pu) in the case of proposed RDCS.

5.2 | Reconfigured case

Initially, all the DGs operate with conventional droop technique. At $t = 4.5$ s, self-adjusting $Q-V$ droop is applied to all DGs and at $t = 19.5$ s the proposed RDCS is applied to all the DGs respectively. The results are as shown in Table 20. $Q_{err}$ in the case of conventional droop is found to be $-109, 23$ and $85$ for DG-1, DG-2 and DG-3, respectively. The self-adjusting $Q-V$ droop reduces the percentage $Q_{err}$ (to $-40, 9$ and $31$ for DG-1, DG-2 and DG-3, respectively) but the overall voltage profile of the network deteriorates and the minimum value of DG output voltage in the network reaches to 0.907 pu. In the case of proposed RDCS, the percentage $Q_{err}$ ($-39, 8$ and $31$ for DG-1, DG-2 and DG-3, respectively) is similar to that of the self-adjusting droop but the overall voltage...
profile of the network improves and the minimum value of DG output voltage in the network increases to 0.944 pu, as shown in Figure 13. The maximum value of DG output voltage in the case of self-adjusting $Q-V$ droop is 0.958 pu which gets improved to 0.999 pu ($\approx$ 1.0 pu) in the case of proposed RDCS.

5.3 | Meshed network

Initially, all the DGs operating with conventional droop control. At $t = 8$ s, self-adjusting $Q-V$ droop technique is applied to all DGs and at $t = 22$ s the proposed RDCS is applied to all the DGs respectively. The results are shown in Table 21. The $Q_{err}$ in the case of conventional $Q-V$ droop is found to be $-110$, $20$ and $90$ for DG-1, DG-2 and DG-3 respectively. The self-adjusting $Q-V$ droop reduces the percentage $Q_{err}$ (to $-38$, $6$ and $32$ for DG-1, DG-2 and DG-3, respectively).

However, the overall voltage profile of the network deteriorates and the minimum value of DG output voltage in the network reduces from 0.957 pu to 0.907 pu. In the case of proposed RDCS, the percentage $Q_{err}$ ($-39$, $7$ and $32$ for DG-1, DG-2 and DG-3, respectively) is similar to that of the self-adjusting droop but the overall voltage profile of the network improves and the minimum value of DG output voltage in the network becomes 0.945 pu which can be seen in Figure 14. The maximum value of
FIGURE 14 Meshed network: \(P/Q\) sharing and output voltages

TABLE 21 Experimental results: Meshed network case

| Droop type       | \(P_{1-3}\)  | \(Q_{1-3}\)  | \(Q_{\text{exp}}\) | \(Q_{\text{err}(1-3)}\) | \(v_{\text{adr}(1-3)}\) |
|------------------|-------------|-------------|-------------------|-------------------|-------------------|
| Conventional     | 597         | \(-14, 165\)| 137               | \(-110, 20\)      | (1.002, 0.972)    |
| droop            | 260         | 90          | 0.957             |                   |                   |
| Self-adjusting   | 542         | 78, 134,    | 126               | \(-38, 6\)        | 0.958, 0.924      |
| droop            | 166         | 32          | 0.907             |                   |                   |
| RDCS             | 587         | 83, 147,    | 137               | \(-39, 7\)        | 1.000, 0.963      |
|                  | 181         | 32          | 0.945             |                   |                   |

DG output voltage in the case of self-adjusting droop is 0.959 pu which gets improved to 1.000 pu by the use of proposed RDCS.

6 | CONCLUSION

A robust droop control strategy (RDCS) based on automatically adjusting the nominal voltage \((V_n)\) has been proposed and validated to improve the voltage profile of the network in a decentralised manner in addition to improved reactive power sharing \((Q_{\text{sh}})\) among the sources in a droop-based microgrid. The proposed technique does not require data communication and information about feeder impedance and network topology. Various case studies by changing the topological structure of the microgrid, including network reconfiguration and mesh formation, have been performed in MATLAB/Simulink to validate the claim. The performance of RDCS has been found satisfactory for improved voltage profile and \(Q_{\text{sh}}\) for all the cases. The viability of the proposed controller (RDCS) for different topological structure has been confirmed from experimental validation on a laboratory-based microgrid prototype.

NOMENCLATURE

- CL: Common load
- \(C_f\): Filter capacitor
- DG: Distributed generator
- \(i_{\text{ad}}\): d-axis output current
- \(i_{\text{aq}}\): q-axis output current
- \(L_f\): Filter inductor
- LL: Local load
- MG: Microgrid
- \(m_p\): Slope of the active power-frequency droop
- \(n_q\): Slope of the reactive power-voltage droop
- \(P\): Active power
- \(Q\): Reactive power
- \(Q_{\text{err}}\): Error in reactive power sharing
- \(Q_{\text{exp}}\): The expected reactive power output from a DG
- \(Q_{\text{sh}}\): Reactive power sharing
- \(R\): Line resistance
- \(R_v\): Virtual resistance
- \(V\): Magnitude of the output voltage of the DG
- \(V_{\text{dc}}\): Input dc link voltage
- \(V_n\): Nominal voltage
- \(v_{\text{adr}}\): d-axis output voltage
- \(X\): Line reactance
- \(X_r\): Virtual reactance
- \(Z_r\): Virtual impedance
- \(\beta, \beta_{\text{adj}}\): Control parameters
- \(\omega\): System frequency
- \(\omega_n\): Nominal frequency
- \(\Delta V\): Voltage deviation
REFERENCES

1. Chandorkar, M.C., et al.: Control of parallel connected inverters in standalone ac supply systems. IEEE Trans. Ind. Appl. 29 (1), 136–143 (1993)
2. Guerrero, J.M., et al.: Advanced control architectures for intelligent microgrids—Part ii: Decentralized and hierarchical control. IEEE Trans. Ind. Electron. 60 (4), 1254–1262 (2013)
3. Han, Y., et al.: Review of active and reactive power sharing strategies in hierarchical controlled microgrids. IEEE Trans. Power Electron. 32 (3), 2427–2451 (2017)
4. Gupta, Y., et al.: A simple control scheme for improving reactive power sharing in islanded microgrid. IEEE Trans. Power Syst. 35 (4), 3158–3169 (2020)
5. Shafiee, Q., et al.: A multi-functional fully distributed control framework for ac microgrids. IEEE Trans. Smart Grid 9 (4), 3247–3258 (2018)
6. Zhou, J., et al.: Consensus-based cooperative droop control for accurate reactive power sharing in islanded ac microgrid. IEEE J. Emerging Sel. Top. Power Electron. 8 (2), 1108–1116 (2020)
7. Mahmood, H., et al.: Reactive power sharing in islanded microgrids using adaptive voltage droop control. IEEE Trans. Smart Grid 6 (6), 3052–3060 (2015)
8. Lee, C., et al.: A new droop control method for the autonomous operation of distributed energy resource interface converters. IEEE Trans. Power Electron. 28 (4), 1980–1993 (2013)
9. Zhou, J., Cheng, P.: A modified $q–U'$ droop control for accurate reactive power sharing in distributed generation microgrid. IEEE Trans. Ind. Appl. 55 (4), 4100–4109 (2019)
10. Fani, B., et al.: An enhanced decentralized reactive power sharing strategy for inverter-based microgrid. Int. J. Electr. Power Energy Syst. 98, 531–542 (2018)
11. Wang, Y., et al.: Distributed optimal control of reactive power and voltage in islanded microgrids. IEEE Trans. Ind. Appl. 53 (1), 340–349 (2017)
12. Dheer, D.K., et al.: A self-adjusting droop control strategy to improve reactive power sharing in islanded microgrid. IEEE Trans. Sust. Energy 11 (3), 1624–1635 (2020)
13. Chen, F., et al.: Multiagent-based reactive power sharing and control model for islanded microgrids. IEEE Trans. Sust. Energy 7 (3), 1232–1244 (2016)
14. Wang, K., et al.: A practical structure and control for reactive power sharing in microgrid. IEEE Trans. Smart Grid 10 (2), 1880–1888 (2019)
15. Kosari, M., Hosseinian, S.H.: Decentralized reactive power sharing and frequency restoration in islanded microgrid. IEEE Trans. Power Electron. 32 (4), 2901–2912 (2017)
16. Zhang, M., et al.: Circulating current control strategy based on equivalent feeder for parallel inverters in islanded microgrid. IEEE Trans. Power Syst. 34 (1), 595–605 (2019)
17. Zhu, Y., et al.: A wireless load sharing strategy for islanded microgrid based on feeder current sensing. IEEE Trans. Power Electron. 30 (12), 6706–6719 (2015)
18. Xu, H., et al.: A reactive power sharing strategy of vsg based on virtual capacitor algorithm. IEEE Trans. Ind. Electron. 64 (9), 7520–7531 (2017)
19. Zhang, J., et al.: Enhanced proportional power sharing strategy based on adaptive virtual impedance in low-voltage networked microgrid. IET Gener., Transm. Distrib. 12 (11), 2566–2576 (2018)
20. Zandi, F., et al.: Adaptive complex virtual impedance control scheme for accurate reactive power sharing of inverter interfaced autonomous microgrids. IET Gener. Transm. Distrib. 12 (22), 6021–6032 (2018)
21. He, J., Li, W.Y.C.: Analysis, design, implementation of virtual impedance for power electronics interfaced distributed generation. IEEE Trans. Ind. Appl. 47 (6), 2525–2538 (2011)
22. Wu, X., et al.: Feasible range and optimal value of the virtual impedance for droop-based control of microgrids. IEEE Trans. Smart Grid 8 (5), 1242–1251 (2017)
23. Zhu, Y., et al.: A virtual impedance optimization method for reactive power sharing in networked microgrid. IEEE Trans. Power Electron. 31 (4), 2890–2904 (2016)
24. Xu, H., et al.: An improved virtual capacitor algorithm for reactive power sharing in multi-parallelled distributed generators. IEEE Trans. Power Electron. 34 (11), 10786–10795 (2019)
25. Wong, Y.C.C., et al.: Consensus virtual output impedance control based on the novel droop equivalent impedance concept for a multi-bus radial microgrid. IEEE Trans. Energy Convers. 35 (2), 1078–1087 (2020)
26. Zhang, H., et al.: Distributed adaptive virtual impedance control for accurate reactive power sharing based on consensus control in microgrids. IEEE Trans. Smart Grid 8 (4), 1749–1761 (2017)
27. Eskandari, M., et al.: Decentralized optimal servo control system for implementing instantaneous reactive power sharing in microgrids. IEEE Trans. Power Electron. 32 (9), 7338–7351 (2017)
28. He, J., et al.: An enhanced islanding microgrid reactive power, imbalance power, and harmonic power sharing scheme. IEEE Trans. Power Electron. 30 (6), 3389–3401 (2015)
29. Zhou, J., et al.: Consensus-based distributed control for accurate reactive, harmonic, and imbalance power sharing in microgrids. IEEE Trans. Smart Grid 9 (4), 2453–2467 (2018)
30. Lin, L., et al.: An improved proportional load-sharing strategy for meshed parallel inverters system with complex impedances. IEEE Trans. Power Electron. 32 (9), 7338–7351 (2017)
31. Pham, D.M., Lee, H.: Effective coordinated virtual impedance control for accurate power sharing in islanded microgrid. IEEE Trans. Ind. Electron. 68 (3), 2279–2288 (2020)
32. Shi, M., et al.: Pi-consensus based distributed control of ac microgrids. IEEE Trans. Power Syst. 35 (3), 2268–2278 (2020)
33. Lou, G., et al.: Distributed mpc-based secondary voltage control scheme for autonomous droop-controlled microgrids. IEEE Trans. Sust. Energy 8 (2), 792–804 (2017)
34. Guo, F., et al.: Distributed secondary voltage and frequency restoration control of droop-controlled inverter-based microgrids. IEEE Trans. Ind. Electron. 62 (7), 4355–4364 (2015)
35. Wu, X., et al.: A distributed, cooperative frequency and voltage control for microgrids. IEEE Trans. Smart Grid 9 (4), 2764–2776 (2018)
36. Schiffer, J., et al.: Voltage stability and reactive power sharing in inverter-based microgrids with consensus-based distributed voltage control. IEEE Trans. Control Syst. Technol. 24 (1), 96–109 (2016)
37. Dheer, D.K., et al.: Effect of reconfiguration and meshed networks on the small-signal stability margin of droop-based islanded microgrids. IEEE Trans. Ind. Appl. 54 (3), 2821–2833 (2018)
38. Pogaku, N., et al.: Modeling, analysis and testing of autonomous operation of an inverter-based microgrid. IEEE Trans. Power Electron. 22 (2), 613–625 (2007)

How to cite this article: Dheer DK, Gupta Y, Doolla S. Decentralised inverter control for improved reactive power sharing and voltage profile in a microgrid. IET Gener Transm Distrib. 2021;15:1227–1241. https://doi.org/10.1049/gtd2.12098