Chapter 9
Power Management of Low and Medium Voltage Networks with High Density of Renewable Generation

M. A. Barik, H. R. Pota and J. Ravishankar

Abstract This chapter presents a review of existing control techniques for load-sharing in low and medium voltage networks. The advantages and major drawbacks of each method are described here. An overall comparison is made to find out the best suitable method for the distribution systems of the future. Finally, the limitations of existing methods and future directions for this research are indicated.

Keywords Microgrid · Load-sharing control · LV and MV networks · Renewable energy sources

9.1 Introduction

The conventional power system uses fossil fuel to generate electrical power which affects the environment [1]. As a result, there is interest in integrating renewable energy sources (RESs) in them [2–4]. RESs are environmental friendly, but some technical challenges must be addressed to integrate RESs with the grid. A major difference from the conventional generation is that RESs are connected to the grid

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via power electronic interface and have low mechanical inertia [1, 5, 6]. Also, RESs are small and distributed throughout the network as distributed generators (DGs) [1]. The integration of DGs into a distribution system reduces the system's power loss, improves its voltage support and increases its efficiency and reliability [7]. On the other hand, automatic load-sharing is an issue with increasing penetration of RESs, because they are inertia-less DGs and connected to the mesh distribution network via inverters [8–11].

Droop control method is a popular way for active and reactive power sharing in a power system. This method has been primarily designed for high voltage (HV) transmission lines and high-inertia based generators. In HV networks, line impedances are inductive, whereas they are resistive in low voltage (LV) and medium voltage (MV) networks. Also, RESs are zero or low-inertia generators. For these reasons, conventional droop-based control does not work well [3, 12]. Thus, it is necessary to develop advanced control techniques for load-sharing in LV and MV networks.

Research studies aimed at improving the load-sharing of LV and MV networks have been conducted. These studies are usually based on modifications of the conventional droop control method. Some studies use communication-based control techniques. In this chapter, an overview of load-sharing in LV and MV networks with high densities of RESs is provided. Firstly, the basic principle and limitations of the conventional droop control method are explained. Then, the results from existing research into mitigating its drawbacks are presented and compared. After that, the load-sharing of LV and MV networks using a communication link is discussed and compared. Afterwards, a droop control-based load-sharing control method with communication is presented and its advantages and disadvantages are highlighted. Some limitations of existing research on the load-sharing of LV and MV networks are determined. Finally, this chapter suggests future directions for overcoming the limitations.

9.2 Load-Sharing Control Techniques for LV and MV Networks

The main objective of load-sharing is to distribute the active and reactive loads among the available DGs while maintaining voltage regulation and accommodating various types of loads [13]. In LV and MV networks, load-sharing becomes challenging due to the following factors.

- Most DGs have some local loads,
- Most DGs are non-dispatchable RESs, and
- The stability and reliability of the system gain importance, apart from the cost.

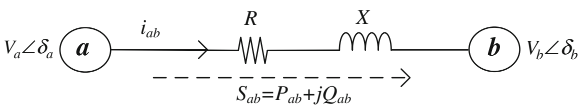

Fig. 9.1 Power flow via transmission line from nodes *a* to *b* [12]

Three different methods of load sharing are commonly employed: droop-based control, communication-based control, and droop-based control with communication link, as described in the following subsections.

9.2.1 Droop-Based Control Techniques

9.2.1.1 Conventional Droop Control Method

A widely used method for load-sharing is the droop control method. A rotating generator's frequency and real power are closely related. Its load torque increases with increasing load, causing its speed to decrease. Thus, its frequency changes with a change in its real load while, its terminal voltage changes with a similar change in its reactive load [14]. The droop control method is based on the concept of controlling the generator's frequency and voltage separately, in order to achieve real and reactive load sharing [5, 15–31]. For an inverter-based generator without a rotating part, better load-sharing can be achieved by the angle droop than the frequency droop method [3, 32]. To explain the droop control method for load-sharing, a complex power flow (S_{ab}) from node *a* to node *b* via a transmission line, as shown in Fig. 9.1, is considered. The equation of the complex power can be written as,

$$S_{ab} = P_{ab} + jQ_{ab} = v_a i_{ab}^* = v_a \left(\frac{v_a - v_b}{z}\right)^* = Y\left(V_a^2 e^{j\theta} - V_a V_b e^{j(\theta+\delta_{ab})}\right) \quad (9.1)$$

where P_{ab}, Q_{ab}, and i_{ab} are the real power, reactive power, and current flow from node *a* to node *b*, respectively, $z = Z\angle\theta = R + jX$ is the corresponding line impedance, $v_a = V_a\angle\delta_a$ and $v_b = V_b\angle\delta_b$ are the voltages of nodes *a* and *b*, respectively, $Y = \frac{1}{Z}$ is the admittance of the transmission line, and $\delta_{ab} = \delta_a - \delta_b$ is the bus angle difference between nodes *a* and *b*. From (9.1), real and reactive power flow can be expressed as:

$$P_{ab} = Y(V_a^2 \cos\theta - V_a V_b \cos(\theta + \delta_{ab})) \quad (9.2)$$

$$Q_{ab} = Y(V_a^2 \sin\theta - V_a V_b \sin(\theta + \delta_{ab})) \quad (9.3)$$

In Eqs. (9.2) and (9.3), it can be seen that the power flows and node voltages are dependent on each other because the line parameters are constant for a given line. Then, these equations can be rewritten for small changes in power flows as:

$$\Delta P_{ab} = Y[(2V_a \cos\theta - V_b \cos(\theta + \delta_{ab}))\Delta V_a + V_a V_b \sin(\theta + \delta_{ab})\Delta\delta_a] \quad (9.4)$$

$$\Delta Q_{ab} = Y[(2V_a \sin\theta - V_b \sin(\theta + \delta_{ab}))\Delta V_a - V_a V_b \cos(\theta + \delta_{ab})\Delta\delta_a] \tag{9.5}$$

For HV transmission lines, line reactances are very high compared to line resistances, that is, $\theta \approx 90°$, $cos\,\theta \approx 0$ and $sin\,\theta \approx 1$. Thus, Eqs. (9.4) and (9.5) can be rewritten as:

$$\Delta P_{ab} = Y[V_b \sin\delta_{ab}\Delta V_a + V_a V_b \cos\delta_{ab}\Delta\delta_a] \tag{9.6}$$

$$\Delta Q_{ab} = Y[(2V_a - V_b \cos\delta_{ab})\Delta V_a + V_a V_b \sin\delta_{ab}\Delta\delta_a] \tag{9.7}$$

Again, as the δ_{ab} is very small, cos $\delta_{ab} \gg$ sin δ_{ab}, Eqs. (9.6) and (9.7) can be modified as:

$$\Delta P_{ab} \approx YV_a V_b \Delta\delta_a \text{ and } \Delta Q_{ab} \approx Y(2V_a - V_b)\Delta V_a \tag{9.8}$$

or

$$\Delta P_{ab} \propto \Delta\delta_a \text{ and } \Delta Q_{ab} \propto \Delta V_a \tag{9.9}$$

Equation (9.9) shows that the real power flow change depends on the bus angle and the reactive power flow change depends on the bus voltage. Thus, load-sharing control can be achieved by independently controlling voltage magnitude(V) and bus angle(δ), as presented in Eqs. (9.10) and (9.11). The characteristics and block diagram of this control scheme are shown in Figs. 9.2 and 9.3, respectively.

$$\delta - \delta_r = -k_p(P - P_r) \tag{9.10}$$

$$V - V_r = -k_q(Q - Q_r) \tag{9.11}$$

where P and Q are the real and reactive powers injection to the grid, V_r, δ_r, P_r, and Q_r are the reference values for the bus voltage, bus angle, real power, and reactive power, respectively, and k_p and k_q are the constants.

9.2.1.2 Limitations of the Conventional Droop Control Method

The conventional droop control method was designed for HV transmission systems in which generators are rotational and transmission lines are inductive. Again, this method was derived from the power flow equation considering X ≫ R. Its performance is very good and very easy to implement [33]. In LV and MV networks, this method becomes ineffective for load-sharing due to the following major drawbacks.

- Most generators are connected to the grid via inverters which are inertia-less and have highly resistive line impedances [3].
- In a highly resistive network, coupling between the *P-f* and *Q–V* droops are unavoidable [34].
- For a large load variation, which is common in LV and MV networks, the transient current is very high [35].

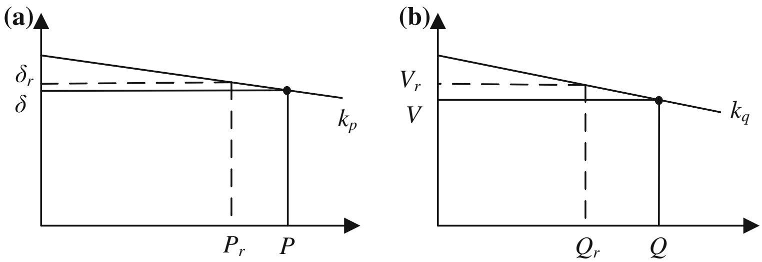

Fig. 9.2 Characteristics of the conventional droop control scheme: **a** P-δ droop, **b** Q–V droop

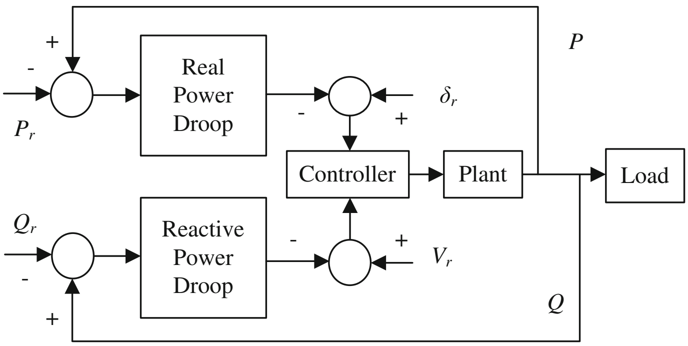

Fig. 9.3 Block diagram of the conventional droop control scheme

- Due to the unequal line impedances, the accuracy of reactive load-sharing decreases [3].
- The majority of DGs have local loads which also decrease the accuracy of reactive load-sharing [3].
- The load-sharing depends on the inverter's output impedance which degrades the performance [34].
- The load-sharing accuracy is low and voltage regulation is poor [36].
- In a weak system, a high gain of the angle droop is required for the proper sharing of load which has negative effects on the stability of the system [37].

9.2.1.3 Modified Droop Control Methods

To overcome the limitations of the conventional droop control method, several research studies have been conducted. Each of the studies has both benefits and drawbacks, as described in the following subsections.

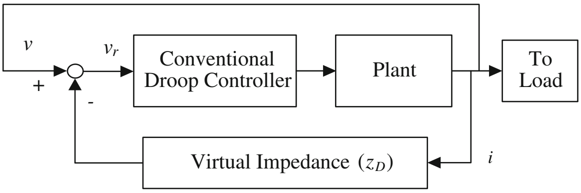

Fig. 9.4 Block diagram of a virtual impedance control scheme [43]

Frame transformation method

The frame transformation technique considers both resistive and inductive line impedances for load-sharing [33, 38, 39]. In this method, an orthogonal linear rotational transformation matrix (T) is used to modify the real and reactive powers as:

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = T \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \frac{X}{Z} & \frac{-R}{Z} \\ \frac{R}{Z} & \frac{X}{Z} \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} \tag{9.12}$$

where P' and Q' are the modified real and reactive powers, and the conventional droop control method is modified by applying this transformation as:

$$\delta - \delta^0 = -k_p\left(P' - P'^0\right) = -k_p\left[\frac{X}{Z}\left(P - P^0\right) - \frac{R}{Z}\left(Q - Q^0\right)\right] \tag{9.13}$$

$$V - V^0 = -k_q\left(Q' - Q'^0\right) = -k_q\left[\frac{R}{Z}\left(P - P^0\right) + \frac{X}{Z}\left(Q - Q^0\right)\right] \tag{9.14}$$

The advantage and major limitation of this method are [40]:

- It improves the real load-sharing accuracy and stability of the system, but
- The reactive load-sharing error exists.

Virtual output impedance method

The coupling between real and reactive load-sharing degrades load-sharing accuracy. An inductor is connected in series with the inverter to improve the sharing accuracy [41], but it is heavy, bulky and costly. This method considers that a virtual impedance (z_D) is connected to the output of the inverter to reduce the imbalance of the line impedance [3, 23, 34, 42–44]. The relationship between the virtual impedance and reference voltage (v_r) is presented in Eq. (9.15) and the control scheme is shown in Fig. 9.4.

$$v_r = v - z_D i \tag{9.15}$$

where i and v are the output current and voltage, respectively.

In this control scheme, the output current is fed via a virtual impedance to improve the voltage regulation which also reduces the coupling between real and reactive load-sharing. This increases the reactive load-sharing error because of increasing droops in the impedance voltage [3]. To improve the accuracy of reactive load-sharing, a method based on an additional control signal is proposed

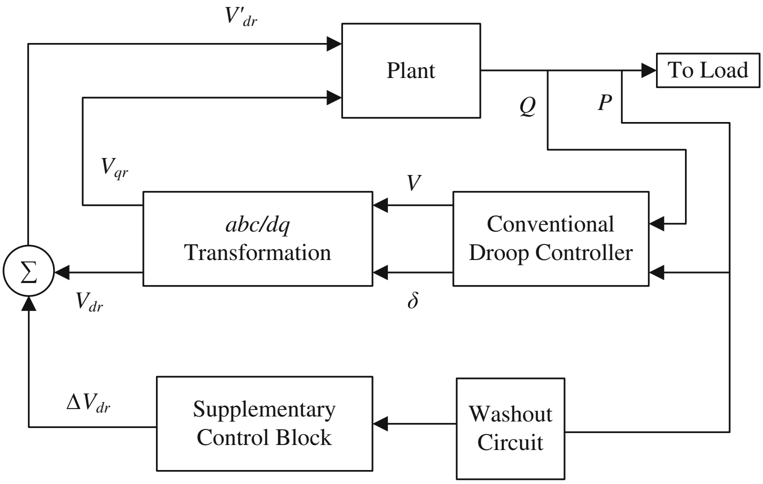

Fig. 9.5 Block diagram of a supplementary droop control scheme, where V_{qr} and V'_{dr} are the q-axis voltage reference and the modified d-axis reference voltage, respectively [37]

in [5]. This method is complex and has a possibility of creating line current distortions. Another approach, which adds $\frac{\Delta V}{Q}$ slopes into voltage droop control, increases the reactive load-sharing accuracy, and reduces the effects of local loads [3]. Another technique is obtained by enforcing the resistive output impedance [34]. This technique offers the advantages of automatic harmonic sharing and improves the dynamic response of the paralleled system. Advantages and limitation of virtual impedance methods are [40]:

- It improves voltage regulation and load-sharing accuracy, and
- It reduces the imbalance of the line impedance, but
- It may not work properly in some situations due to the plug-and-play features of DGs and loads.

Supplementary control loop method

In a weak system, the high gain of the angle droop controller is required for the proper sharing of load causing a stability problem in the system. A supplementary control scheme is presented in [37]. This scheme considers closed-loop stability over a range of operating conditions. Also, its reduces the effect of the high gain by using a supplementary loop with conventional droop control as shown in Fig. 9.5. In this method, the output real power from the inverter passes through a high-pass washout circuit with a 0.05 s time constant to capture the oscillatory behaviour and eliminate the DC component. The supplementary control block generates a supplementary control signal (ΔV_{dr}) which modulates the output from the droop controller to modify the d-axis reference voltage (V_{dr}). This method is based on the local measurement and modulation of the d-axis voltage reference of each inverter. Finally, the supplementary loop increases the operating range of a weak system to

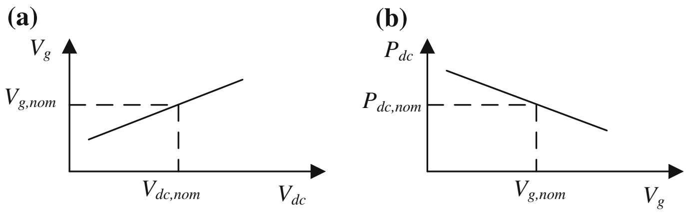

Fig. 9.6 **a** *Vg/Vdc* droop, **b** *P/Vg* droop [46]

ensure satisfactory load-sharing. Its advantages are increase in the operating range and reduction of the load-sharing error. However, this method considers only the stability issue.

Voltage-based droop control method
In an inertia-based generator, the power imbalance affects the frequency of the generator which can be managed by controlling this frequency. In an inverter-based generator, the power balance is achieved by controlling the DC-link voltage. Also, the power flow in a distribution network depends on the voltage magnitude due to the network's highly resistive transmission lines. Based on these, a voltage-based droop control scheme with two parts, a V_g/V_{dc} droop and a P/V_g droop, is presented in [1, 45, 46] and shown in Fig. 9.6. In the V_g/V_{dc} droop, the RMS value of the terminal voltage (V_g) changes according to the change in the DC-link voltage (V_{dc}) as:

$$V_g = V_{g,nom} + m(V_{dc} - V_{dc,nom}) \tag{9.16}$$

where $V_{g,nom}$ and $V_{dc,nom}$ are the nominal values of the RMS voltage and DC-link voltage, respectively and m is a constant. Again, voltage variations can occur due to the control action taken by the V_g/V_{dc} droop. In every system, there is a certain tolerance level for voltage variation. If it is exceeded, the output power from the DGs is changed by the P/V_g droop. This controls the DC-link power (P_{dc}) which depends on the constant power bandwidth of the DGs, as shown in Fig. 9.7. The advantages and disadvantages of this method are:

- It improves sharing accuracy and voltage regulation,
- It is more beneficial for delaying RESs' power changes than a dispatchable unit which encourages the integration of more renewable energy, and
- It opposes hard curtailment which reduces ON–OFF oscillations, but
- It does not address the reactive power-sharing accuracy.

9.2.1.4 Comparison of Modified Droop Control Methods

All the modified droop control methods for the proper sharing of load in a distribution system improve sharing performance. In the frame transformation

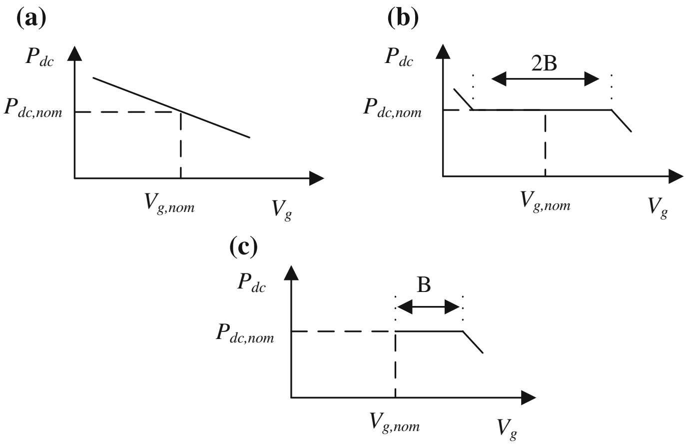

Fig. 9.7 Constant power bands: **a** dispatchable unit (no bandwidth limit), **b** less dispatchable unit (bandwidth = 2B), and **c** non-dispatchable unit (bandwidth = B), where $P_{dc,\ nom}$ is the nominal value of the DC-link power [1]

method, load-sharing is improved by considering both resistive and inductive line impedances. A reactive load-sharing error exists in this method due to the coupling between real and reactive load-sharing. The virtual output impedance method reduces the effect of unbalanced line impedance and increases load-sharing accuracy. Sometimes this method may not work properly due to the plug-and-play features of DGs and loads. On the other hand, stability can be improved by adding a supplementary control loop to the supervisory control loop. Finally, voltage-based droop control method considers all the generator types, such as dispatchable, non-dispatchable and inertia-less DGs, and considers resistive transmission lines while encouraging the integration of more RESs. This method is more suitable for load-sharing in a distribution system because it considers the system's maximum constraints. Also, it highlights the sharing accuracy of the real power, but it does not address that of the reactive power very well.

9.2.2 Communication-Based Control Techniques

9.2.2.1 Centralised Control Schemes

In these control techniques, load-sharing is centrally controlled by coordinating all DGs and loads, with a central control unit measuring the load demand of the system. A communication link sends reference signals to the local controllers which are responsible for controlling the generating unit to meet the reference value. There are two centralised control techniques, the central limit and master, which are described in the following subsections.

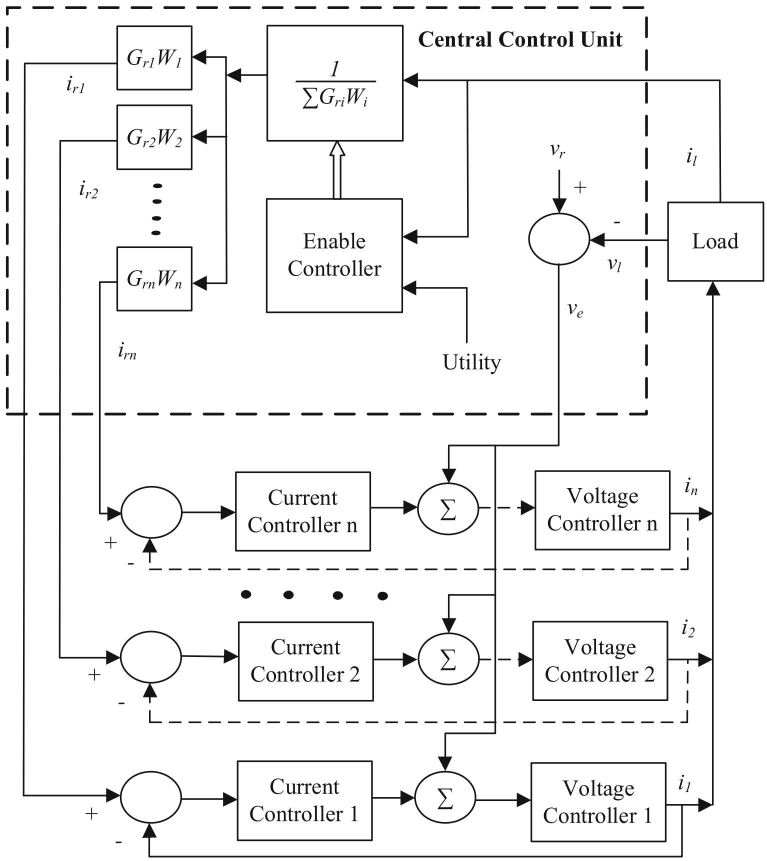

Fig. 9.8 Block diagram of a central limit control scheme [47]

Central limit control scheme

The central control unit measures the real and reactive load values and load voltages, and calculates the reference currents (i_r) for each generator and the voltage error term (v_e). The central limit control scheme is presented in Fig. 9.8. The reference current for a generator can be calculated by dividing the total load current (i_l) by the weighting factors (W) of the generators, i.e., the summation of all the reference currents is equal to the load current, where the weighting factors depend on the ratings of the generators (G_r). The voltage error term can be calculated by comparing the load voltage (v_l) with the reference voltage (v_r). Local controllers control the output currents and terminal voltages by considering the reference current and voltage error [47–49]. A phase-lock loop (*PLL*) is used to synchronise the central control unit and local controllers. This method has some superior characteristics and also some limitations, as described below [35, 48–50].

- Its control algorithm is very simple.
- Current-sharing is forced during all times, including transients.
- Accurate load-sharing and voltage regulation are achieved in the steady state as well as during transients.
- The communication links and supervisory control centre required are expensive.
- It is difficult to apply in a large and highly distributed system especially during system expansion.
- It is difficult to achieve a fast response for power distribution control due to the relatively slow response of the PLL.
- Neglecting the line impedances in the control strategies is a significant disadvantage.
- If the sum of the weighting factors differs from one due to reasons like the shutdown of a unit or a programming fault, the load current will not be supplied properly.

Master control scheme

This technique is almost the same as the central limit control technique [48], where all the local control units control both the voltage and current. In master control scheme, master unit is responsible for only the voltage regulation. The load current is divided among the other units according to their weighting factors. An advantage of this method is that the master unit can provide transient current at the time of a wrong weighting factor because it does not have a current controller.

In this control scheme, the master unit can be selected as a fixed, arbitrarily chosen or maximum crest current unit and in the grid-connected mode, the main grid can be used. Another option in this method is that the master unit can take the responsibility of a central control unit and operate as a voltage source inverter. In this case, master unit measures the load demand of the system, controls the grid voltage, calculates the reference current for each generator and sends it to the relevant generator. This technique has some advantages over the central limit control approach as well as some disadvantages, as given below [35].

- In the case of failure of a unit, the system will still be operational because the master unit will supply the transient current.
- Its load-sharing performance is good because the master unit controls the grid voltage while other units are responsible for controlling only the output current.
- At a time, one signal has to be distributed to each local controller.
- It can operate without a central control unit.
- As the instantaneous voltages and currents are distributed throughout the system, a high bandwidth is required for communication.
- The system will not work if the master unit fails because all the other units depend on it.
- A high transient current can cause a dangerous situation because the master unit does not have any current controller.
- As a relatively higher bandwidth is required in the transient than steady-state condition, the system can fail if it has a low bandwidth.

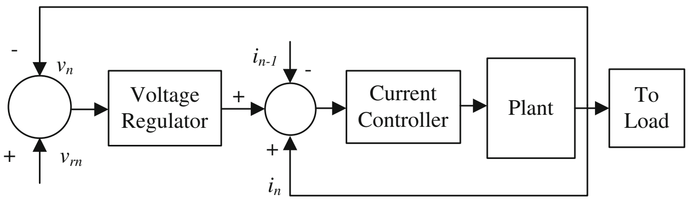

Fig. 9.9 Block diagram of 3C scheme [13]

9.2.2.2 Circular Chain Control (3C) Scheme

The 3C method is presented in [13]. In this method, each module tracks the output current from the previous module, with the first modules tracking those from the last as reference values to share equal current, as depicted in Fig. 9.9. The voltage control loop is used to ensure voltage regulation. This method requires less communication than other techniques because each module communicates with only the previous one and its dynamic response is very fast. Its advantage and major drawback are:

- It requires less communication, but
- All units must be successively connected.

9.2.2.3 Distributed Control Through Frequency Partition

The distributed control technique is based on frequency partitioning between the central and local controllers [50, 51]. The central controller is responsible for controlling the low-frequency term and the local controllers the high-frequency term. Information on the modules' voltage references, current references and average feedback voltages is shared among the modules. This scheme presents a control algorithm which combines a low-pass filter (H_{LF}) with a matched high-pass filter ($1-H_{LF}$). The filters are used for perfect sharing of the control spectrum between two controllers, as depicted in Fig. 9.10. This control scheme uses a limited bandwidth of the communication signal. Its advantages and disadvantages are [35, 50]:

- Transient load-sharing is improved,
- The system will continue to run if a module breaks down,
- A limited bandwidth communication link is used to maintain load-sharing between the units,
- The local controller rejects the harmonic component, and
- The power quality of the system is improved under linear, nonlinear, balanced and unbalanced loads, but
- Interconnections between the DGs are required, and
- Higher performance can be achieved with high bandwidth which is costly.

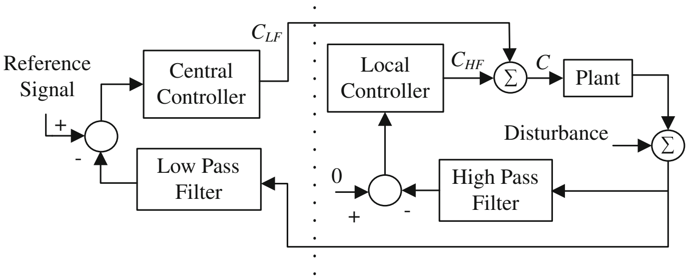

Fig. 9.10 Block diagram of a distributed control scheme, where C is the control signal [51]

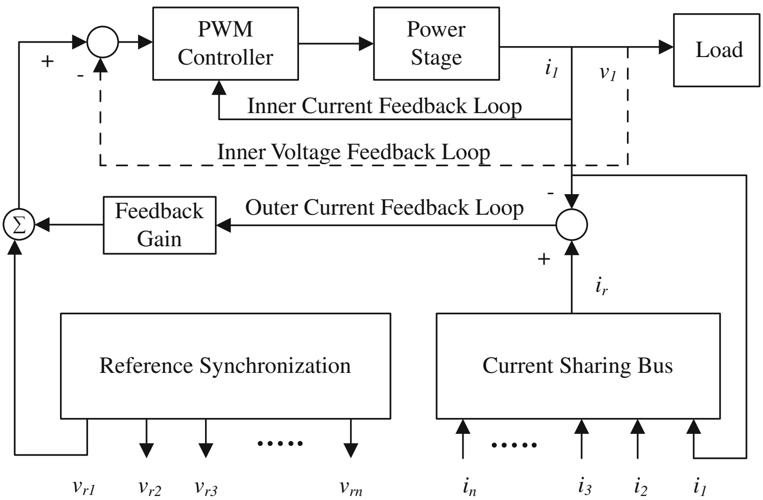

Fig. 9.11 Block diagram of an instantaneous average current-sharing control scheme [53]

9.2.2.4 Instantaneous Average Current-Sharing Scheme

For proper load-sharing control, the RMS values of the output currents are shared among the modules [26] and the average active and reactive loads shared [52]. These methods have good performances, but their current-sharing responses are very slow [53]. To overcome this issue, an instantaneous average current-sharing scheme based on sharing the instantaneous average current values among the inverters was designed [53–56]. In this method, a current-sharing bus measures deviations of the individual output currents and generates a current reference value for all DGs, as shown in Fig. 9.11. The voltage reference of each generator is different, but synchronisation is required to make the voltage phase angles of all inverters the same to ensure equal load-sharing. Each inverter has three control loops, inner current, outer current and inner voltage. The inner voltage and current loops control the inverter to provide good sharing in both steady-state and transient conditions for each single inverter. The outer current loop ensures equal sharing of the load by each inverter. This method is improved by introducing an adaptive gain-scheduling approach that modifies the current error signal [54]. The advantage and limitations of this method are [35]:

- It performs well for both current-sharing and voltage regulation, even if the output currents contain many harmonics, but
- The necessary interconnections between the inverters limit the flexibility of the system and degrade redundancy,
- The highest current control deteriorates the current distribution and output voltage regulation,
- The non-identical component characteristics and input voltage variations of the paralleled inverters might also deteriorate system performance, and
- This method is designed for equal power-sharing only.

9.2.2.5 Comparison Between all Communication-Based Methods

Various types of communication-based control techniques proposed for sharing the load in a distribution system perform better than the droop control method. These methods need a communication link, which is expensive, and interconnections among all modules, which reduces the reliability of the system. Of all the communication-based methods, the centralised control ones are the most simple and accurate for sharing the load among DGs in LV and MV networks. They are expensive and difficult to implement in a complex system. The 3C method offers a simple control with less communication and has a first dynamic response, but requires successive connections of all DGs which may not visible in practical cases. The instantaneous average current-sharing control scheme controls the output current from each generator by measuring the deviations of individual output currents to ensure equal sharing of the load currents. This method only produces good results for equal current-sharing. Finally, distributed control through the frequency partition method performs well in terms of load-sharing under both steady-state and transient conditions. Also, this method is effective for linear, non-linear, balanced, and unbalanced loads. Its performance depends on the communication bandwidth. A high bandwidth would achieve better performance. As this is costly, this method considers a limited bandwidth communication link for communicating with all DGs.

9.2.3 Droop Control Method with Communication

The main limitation of the droop control method is the coupling between real and reactive load-sharing which decreases the sharing accuracy. The high cost of a communication link is the major drawback of the communication-based control

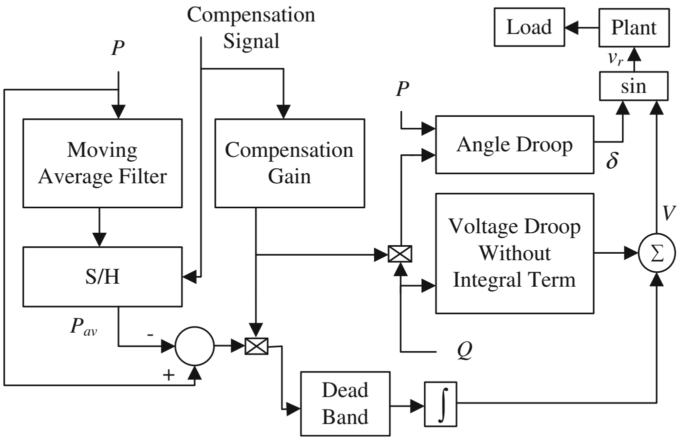

Fig. 9.12 Block diagram of a reactive power compensation control scheme [40]

method. Considering these constraints, a method is proposed in [40] which achieves good load-sharing at a relatively low communication link cost. This is a reactive power compensation scheme based on the droop control method. This scheme uses a low bandwidth synchronisation flag signal to obtain the reactive-sharing error from the central controller.

A reactive power compensation control scheme for load-sharing in LV and MV networks is shown in Fig. 9.12. Here, load-sharing is undertaken by coordinating the central and local controllers. The central controller measures the reactive load-sharing error and transmits it to the local controllers via a uni-directional low-bandwidth communication link. Initially, each local controller uses the conventional droop control method for load-sharing and measures the average power (P_{av}). Each local controller stores the average power until it receives an error signal from the central controller. Then, a modified droop control method is used to compensate the reactive load-sharing as:

$$\delta - \delta^0 = -(k_p P + k_q Q) \tag{9.17}$$

$$V - V^0 = -k_q Q + \int k_i (P - P_{av}) \tag{9.18}$$

where P_{av} is the last value of the average active power saved before the error signal is received. In Eq. (9.17), angle droop control is achieved by coupling the real and reactive powers in the case of a reactive power error, where $k_q Q$ is used as an unequal offset and is present only for a compensating reactive power-sharing error. The integral term in Eq. (9.18) is used to maintain the active power at P_{av} during the time of reactive power compensation. A dead band is used before the integral block to limit the impact of load variations during that period. The advantages and disadvantages of this method are:

- A low bandwidth uni-directional flag signal is used to obtain the reactive power error signal from the central controller,
- Local load effects, unequal voltage drops in virtual and physical impedances, and variations in droop slopes are considered, and
- Its reactive load-sharing accuracy is very good like its frequency droop in the steady state, but
- Measuring the average power is not straightforward, and
- Its transient performance is not very good, particularly for a sudden large load variation.

9.3 Conclusions and Future Directions

An appropriate technique for controlling generating units in a distribution system to ensure the proper flows of real and reactive powers while maintaining the stability of the system is required. Designing a control scheme for load-sharing in a distribution system is a big challenge because its transmission lines are resistive, line impedances are unequal, most of its DGs are inverter-interfaced with some local loads, and it is based on inertia-less RESs which have significant effects on load-sharing.

A brief discussion of existing research on load-sharing of LV and MV networks is presented in this chapter. Existing research shows that the load-sharing of the distribution system can be enhanced by modifying the conventional droop control method, using communication link, or using modified droop control method with communication link. In all approaches, load sharing performance is improved. Among them, communication-based methods achieve better performance for load-sharing as well as better voltage regulation. These methods have not achieved popularity due to high cost of the communication link and the complexity of implementation. Most of the present research focuses on modifying the droop control method for load sharing. Existing modified droop control methods give a significant better performance on load-sharing, but reactive power-sharing accuracy, of the modified droop control methods, needs a significant improvement for practical applications. Finally, droop-based control method with communication link improves reactive power sharing accuracy, but advanced technique is required to ensure the fast transient response.

Overall, it can be concluded that the major limitation of existing research is that its results in terms of reactive power-sharing accuracy in the transient condition are not up to the mark, but could be improved by adding some extra features using the reactive power compensation method, such as:

(1) a better tuning algorithm for selecting the controller gain to reduce compensation time,
(2) a scheme for predicting loads and generation capability in advance, and
(3) a robust controller which has a better transient response capability.

Appendix-I: List of Symbols

Symbols	Variable names
s_{ab}	Power flow from node *a* to *b*
P_{ab}	Real power flow from node *a* to *b*
Q_{ab}	Reactive power flow from node *a* to *b*
i_{ab}	Current flow from node *a* to *b*
R	Line resistance
X	Line reactance
z	Line impedance
Z	Magnitude of the line impedance
θ	Phase angle of the line impedance
Y	Line admittance
z_D	Virtual impedance
v	Terminal voltage/output voltage of a generator
v_a	Voltage of node *a*
v_b	Voltage of node *b*
v_r	Reference voltage of a generator
v_l	Load voltage
v_n	Terminal voltage of the *n*th generator
v_e	Voltage error term
V	Terminal voltage magnitude
V_a	Voltage magnitude of node *a*
V_b	Voltage magnitude of node *b*
V_r	Reference value for V
V_g	RMS value of terminal voltage
V_{dc}	DC-link voltage
V_{dr}	Direct axis voltage reference
V_{qr}	Quadratic axis voltage reference
$V_{g,\ nom}$	Nominal value of RMS voltage
$V_{dc,\ nom}$	Nominal value of DC-link voltage
ΔV_{dr}	Supplementary control signal for modifying direct axis voltage reference
V'_{dr}	Modified direct axis voltage reference
δ	Bus angle
δ_a	Bus angle of node *a*
δ_b	Bus angle of node *b*
δ_r	Reference value for δ
δ_{ab}	Bus angle difference between nodes *a* and *b*
i	Output current of a generator
i_r	Reference current
i_l	Total load current
i_n	Output current of the *n*th generator
P	Real power injection to the grid
Q	Reactive power injection to the grid
P_r	Reference value for P
Q_r	Reference value for Q

(continued)

(continued)

Symbols	Variable names
P'	Modified real power injection to the grid
Q'	Modified reactive power injection to the grid
P_{dc}	DC-link power
P_{av}	Average power
$P_{dc,\ nom}$	Nominal value of DC-link power
G_r	Rating of generator
W	Weighting factor of the generators
C	Control signal
C_{LF}	Control signal from central controller
C_{HF}	Control signal from local controller
m, k_p and k_q	Constants

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