A Review on Primary and Secondary Controls of Inverter-interfaced Microgrid

Kafeel Ahmed, *Member*, *IEEE*, Mehdi Seyedmahmoudian, *Member*, *IEEE*, Saad Mekhilef, *Senior Member*, *IEEE*, N. M. Mubarak, and Alex Stojcevski, *Senior Member*, *IEEE*

***Abstract*—The demand of electricity and environmental issues associated with conventional power generation plants are increasing significantly. Modern technology has transformed the conventional power system through the integration of distributed generation (DG). With the help of modern power electronic technology, the conventional power system is able to support the integration of DGs based on renewable energy sources (RESs). The systematic combination of DGs with energy storage system forms a microgrid (MG), which can operate in islanded mode or grid-connected mode. The intermittent nature of RES and varying load pose substantial obstacles such as voltage and frequency instability, and the unreliability of RES. Unequal feeder impedances and non-linear loads are considered as present challenges in MG control. Hierarchical control has been useful in undertaking solutions to these issues. This paper covers the deep insight of different control methods applied at the primary and secondary control levels in hierarchical control. In primary control, the classification based on droop and non-droop controls is discussed. The virtual synchronization machine (VSM) based control method is reviewed. Voltage and frequency restoration control and economical operations at decentralized and centralized secondary control are analyzed in detail. Based on the existing literature, critical discussion on MG control and future trends are also presented to provide future research perspectives.**

***Index Terms*—Distributed generation (DG), hierarchical control, droop control, non-droop control, inverter.**

I. INTRODUCTION

THE electricity generation in the conventional power system relies on the forecasted data, and the electricity distribution has been passive for a long time. However, cutting-edge technology is proven to be promising for conventional power systems with the concept of distributed generation (DG), which is mostly based on renewable energy sources (RESs). The technology integrates the communication, advanced control and management to profile modern power systems equipped with DG units based on either RES or other sources [1]-[3]. The micro-sources such as micro-turbines, low-power wind turbines, and photovoltaic (PV) cells are considered as DGs integrated into the power system.

There are many advantages for both consumers and utility with the integration of DGs in the power system, particularly the cost-saving. However, the penetration of a large number of DGs into the system may cause problems in low-voltage distribution networks such as bidirectional power flow, voltage deviations, and voltage fluctuations [4]. However, these issues can be fixed when a combination of DG and distributed storage (DS) units is utilized [5], [6]. When DG and DS units are organized systematically, they form a microgrid (MG) [7]. MG provides more capability and flexibility compared with a single DG integrated into the power system. To maintain the standard values of system parameters and to ensure the reliability of the MG during the integration of new DG units, it requires to have "plug-and-play" characteristics [8], and replicates the synchronous generators (SGs) connected in parallel. The frequency and voltage control methods are employed to control the active and reactive power [9], [10]. Thus, the "plug-and-play" characteristic does not require any modification in the applied control system for the addition of new DG units or the disconnection of the existing DG units.

The basic structure of MG is shown in Fig. 1 [7]. It may consist of multiple DG units, DS units, and different types of loads connected to MG through various points of connection (PCs). In grid-connected mode, the power flow between utility and MG is established through the point of common coupling (PCC), which also provides protection and isolation from the main grid in case of faults. The DGs with DC outputs such as PV systems and DS units deliver power through power converters, i.e., DC-DC and DC-AC. However, DG units with AC outputs are coupled through AC-DC and DC-AC power converters. In islanded mode, DG and DS units supply power only to the locally connected load of the MG.

Hierarchical control is applied to ensure the reliable and economic operation of the MG, which has three control levels, i.e., primary, secondary, and tertiary [11]. These control levels have different response times and require communica-

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K. Ahmed, M. Seyedmahmoudian, S. Mekhilef, and A. Stojcevski are with the School of Software and Electrical Engineering, Swinburne University of Technology, VIC 3122, Victoria, Australia, and S. Mekhilef is also with the Power Electronics and Renewable Energy Research Laboratory, Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia (e-mail: kafeel_kalwar@yahoo.com; mseyedmahmoudian@swin.edu.au; saad@um.edu.my; astojcevski@swin.edu.au).

N. M. Mubarak (corresponding author) is with the Department of Chemical Engineering, Faculty of Engineering and Science, Curtin University of Technology, 98009 Sarawak, Malaysia (e-mail: mubarak.yaseen@gmail.com).

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tion [12]. From the prospect of the power system, two types of control methods are applied, i.e., centralized and decentralized [13]. A centralized control requires the communication between the central controller and the local controller of each DG unit. Based on the collected data from the local controller, control actions are determined at the central controller and communicated back to the local controller for execution. However, in decentralized control, each DG unit is controlled by the local controller, which does not require the communication with other units. In decentralized control, the local controllers are unaware of system-wide faults. Primary control has the shortest response time, and it does not require communication when used in the decentralized system. However, it requires communication when applied in centralized control, distributed control, and master-slave control [14]-[16]. This control is responsible for the regulation of frequency and voltage at the inner loop of control. Due to its shortest response time, it also takes care for the islanding detection, power sharing and output power control of DGs [17], [18]. Droop control is mostly used at the primary control level that emulates the characteristics of interconnected SGs and ensures the desired power sharing between DG units without communication [19]-[22]. There are limitations of droop control particularly in power sharing under uncertain output impedances and dynamic load conditions [23]. Energy storage can help the droop control for power sharing under these conditions, but it compromises the aspect of voltage regulation. The limitations are countered by secondary control. However, if primary control is based on communication, for the systems mentioned above, it offers better voltage regulation and transient response under system dynamics and harmonic sharing. Secondary control has longer operation time than primary control, as it minimizes the frequency and voltage deviations that persist even after the execution of primary control [24]-[26]. Secondary control can also be used for both centralized and decentralized controls. In centralized control, the secondary control is carried out by a central controller of the MG. However, in decentralized control, it is executed by local controllers. This control level may include the objectives of reactive power sharing, power quality, synchronization with utility, etc.

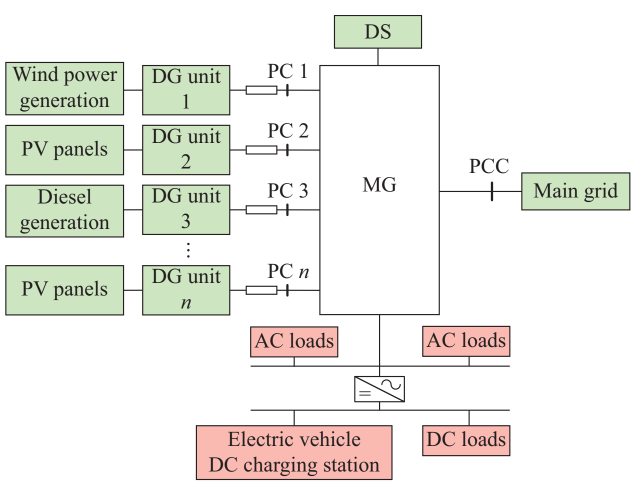

Fig. 1. Basic structure of MG.

The objective of this paper is to identify the existing control methods applied at the primary and secondary control levels, and the following insight of review and future research areas are to be established. Section II describes the operation of the MG in both grid-connected and islanded modes. Section III provides a brief discussion on hierarchical control of the MG. Section IV presents the methods of primary control and their challenges in detail. Section V covers the techniques of secondary control and their problems. In Section VI, based on the literature, a critical discussion on MG control has been presented. Future trends have been discussed in Section VII. Finally, Section VIII concludes the paper.

II. Operation of MG

The MG operates in either grid-connected or islanded mode [7], [27]. It is preferable that an MG should operate in both modes to obtain the maximum benefits. However, due to safety reasons and standards, the utilities do not allow the operation in the islanded mode unless a fault occurs in the MG [28]. The performance of the overall system in grid-connected mode relies on the precisely measured voltage and frequency of the main grid. The islanded mode operation, without support from the main grid, requires a robust control to maintain standard voltage, frequency, and balanced power sharing [29].

A. Islanded Mode

The MG switches from grid-connected mode to islanded mode for a number of reasons such as fault occurrence, scheduled maintenance on the utility side, and cost effectiveness. For the last reason, the MG is disconnected deliberately from the main grid for economic dispatching and cost reduction of electricity provided to local loads. To standardize the islanding, reconnection, and transition between the two modes, the compliance of the IEEE 1547 standard guidelines has to be ensured in the MG control [30]. In islanded mode, the MG is not supported by the utility and requires the control of power converter that establishes and regulates system frequency and voltage. The power converter follows the principle of grid forming, and the references for voltage and frequency control loops are determined by secondary control. The reliability of the MG is affected by its low-inertia characteristic which can cause an outage in case of low power generation or increase in demand [27]. When the critical loads are connected to the MG in the islanded mode, voltage quality control is essential that should maintain low total harmonic distortion (THD) in various load scenarios. Thus, the DS device can help maintain the system frequency and voltage as well to compensate for the fluctuations caused by variable power outputs and unstable load patterns [5], [6]. The devices may include batteries, super-capacitors, etc. The MG has to generate excessive power than the demand to maintain a power balance in storage devices.

The control techniques based on communication or those without communication can be used for islanded mode operation of the MG [31]-[36]. However, it is economically viable and reliable to use the control technique which does not require communication for its operations. Since the MG does not receive any reference in islanded mode, the applied control should operate DG units in voltage source inverter (VSI) mode for maintaining standard voltage and frequency. Master-slave control is widely used in islanded control of MG, which connects DG units positioned in near vicinity to each other through a common bus [37], [38]. In this control, one of DG units operates as a master and the rest as slaves. The master unit is responsible for maintaining voltage and frequency, and thus provides reference signals for the slave units. The master unit operates in VSI mode, whereas the slave units operate in current source inverter (CSI) mode to ensure the equal distribution of current. The control methods used in this mode are either based on droop concept or uses communication. However, both the types are dependent on local measured variables [31].

B. Grid-connected Mode

In this mode, the PCC connects the MG to the main grid, and there is power flow through this tie line. The MG controller ensures the power flow from the MG to the utility if the generated power of DG units is surplus. However, it also imports power from the main grid when the generated power is less than the local demand. In grid-connected mode, the power converter operates by using a grid-following principle, where the main grid provides the references of voltage and frequency to the DG units in MG. Thus, current control is applied on power converter which determines the values of active and reactive to be injected into the main grid [39]. The transients caused by faults in the main grid or due to load fluctuations produce harmonics, which can flow bidirectionally from the main grid to the MG and vice versa. Thus, the filter with inverter-side inductor, filter capacitor, and grid-side inductor (LCL) is used to block unwanted components of parameters on both sides.

The control in this mode uses any natural, stationary, and synchronous references. By applying phase-locked loop (PLL) or frequency-locked loop (FLL) with its respective reference frameworks, it synchronizes the key parameters of the main grid with the MG [40]. Droop control is widely used in the grid-connected mode of the MG to regulate the power injected into the main grid by controlling the power angle. Unlike the control of conventional inverters using output current as feedback to obtain better regulation and lower THD, the droop control does not entail the current directly. Droop controls *P-f/Q-V* and *P-V/Q-f* are chosen for the inductive and resistive types of the MG, respectively [41]. Droop control with an integrator has been studied to improve the precision of power flow. Various modified droop controls have been investigated to improve the dynamic response and precise power control [42] - [45]. Master-slave control, as a central controller, can be applied in this mode where the main grid operates as a master unit. It is responsible for deciding and maintaining the voltage reference [46]. It also allocates the values of current reference to other slave units in the MG to ensure the required supply of active and reactive power.

III. Hierarchical Control of MG

Generally, the MG consists of different DG units, some of which are based on renewable energy and others based on the conventional power generation, i.e., diesel generator. All these sources have different power generation capacities, costs of electricity generation, and degrees of reliability. Thus, the MG requires hierarchical control to host the interconnected system of DG units to ensure the desired power sharing, reduce the cost of generation, and increase the reliability and efficiency of the system [47].

Figure 2 shows the hierarchical control, which is a well-known MG control consisting of three control levels, i.e., primary, secondary, and tertiary [24], [48]. The primary control takes care of frequency and voltage regulation in the inner loop and gathers the data of variables locally, which does not need communication when used in a decentralized power system. It employs droop control and virtual impedance control at each DG unit for output power regulation [16], [32], [49], [50]. In centralized control, the primary control varies the output of each DG unit, keeping in view their capacities determined from the instructions of central control [51], [52]. These instructions are passed from the secondary control to primary control, which is responsible for reducing the frequency and voltage deviations that persist even after the execution of the primary control. It works as centralized control and thus coordinates the information among DG units through communication devices. It ensures the voltage profile maintained across AC buses in the MG, and keeps updating the DG units for system-wide variables all the time. That is why the time response of the secondary control is longer than that of the primary control, as shown in Fig. 2. The primary control has bandwidths of 5 kHz and 20 kHz for current control and voltage control, whereas the secondary and tertiary controls have bandwidths of 30 Hz and 3 Hz, respectively. In most of the small-scale or remotely-established MG systems implemented in real time, the centralized control methods are not preferred, which involve the communication at the secondary or tertiary control level. For such applications, the communication adds extra cost and complexity in the control systems, whereas the primary control can be an automated control based on the local voltage and frequency measurements [53].

The tertiary control takes the data of connected load, demand and supply balance, weather forecast, and economic dispatching into consideration to optimize the MG operation for reducing the cost of electricity units and increasing reliability [12]. Once the data is incorporated, the tertiary control sets the references of power output for each DG unit, which communicates to the primary control level through the secondary control. The tertiary control level takes more time than the primary and secondary control levels, ranging from a few to several minutes [53], [54]. It supports the secondary control in case of unplanned system transients. When the MG operates in grid-connected mode, the tertiary and secondary controls involve the coordination between grid and grid-supporting/grid-feeding power converter. These converters feed the specified active and reactive power, as the frequency and voltage are determined by high-level control.

Whereas in the islanded-mode or resynchronization phase, the main objective of the DG control is to regulate the frequency and voltage within the prescribed limits. The grid-forming converter is used in stand-alone mode, which governs the frequency and voltage through local control. The control techniques that have been used at these hierarchical levels are presented in Table I [12], [55], [56].

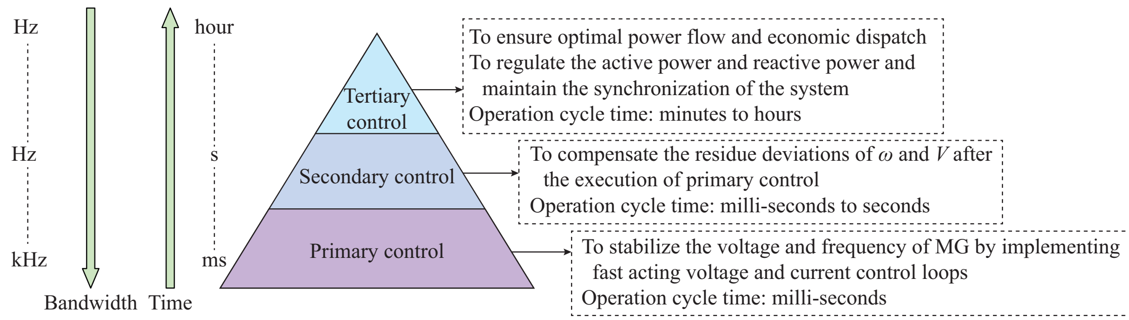

Fig. 2. Hierarchical control of MG.

TABLE I
CONTROL TECHNIQUES APPLIED TO HIERARCHICAL CONTROL

Control level	Control technique	Objective
Primary	Conventional droop control, i.e., *P-f/Q-V* or *P-V/Q-f*, compensated droop control, modified *P-V* droop with *Q-f* boost (VPD-FQB) control, adjustable load sharing control, adaptive voltage droop control, virtual frame transformation, signal injection, centralized control, average load sharing control, non-linear load sharing, master-slave control, etc.	To ensure accurate power sharing among DG units connected in parallel To stabilize the voltage and frequency of the MG To avoid the circulating current between DG units
Secondary	Genetic algorithm (GA), particle swarm optimization (PSO), ant colony optimization (ACO), model predictive control (MPC), multi-agent system (MAS) concept, potential function-based control, voltage unbalance compensation technique, gossip-based technique, distributed cooperative control, etc.	To compensate for the error in voltage and frequency stability leftover by primary control To ensure the operation of energy management system (EMS)
Tertiary	Game theory based technique, equal marginal cost based technique, gossip-based technique, etc.	To coordinate MGs with the main grid To determine operation points of DG units considering economic aspects of the electricity market, unit tariffs, etc.

The MG consists of RESs whose output is intermittent and unpredictable over time. This causes forecasting inaccuracies that could affect the functions of tertiary control. Thus, the decisions taken at the tertiary control level for economic dispatching of DG units become uneconomical for the MG. Moreover, small-scale MG projects in real time would prefer the function of tertiary control merged with the secondary control. Some studies suggest the merger of secondary and tertiary controls as a solution to these issues, because it could reduce the operation time of control [53], [54], [57]-[59].

IV. PRIMARY CONTROL

As mentioned in the above section, the primary control is the lowest control, which provides the inverter output control and power sharing control. The inverter output control consists of the inner loop and outer loop. The outer loop regulates the voltage whereas the inner loop controls the output current [60]. The inverter control employs a suitable reference frame, i.e., synchronous (*dq*), stationary ($\alpha\beta$), or natural (*abc*) [61]. The synchronous reference frame is used if the control is based on proportional-integral (PI) controller, or it deals with DC variables only. However, it uses a stationary reference frame when dealing with sinusoidal variables or proportional-resonant (PR) controller. The hysteresis, deadbeat, PR, and PI controller use the natural reference frame [62]. Most commonly, the inverter output control is implemented with PI controller. To improve the dynamic performance of the controller, it uses feed-forward compensation [61], [63]. To enhance the performance of the control in the presence of nonlinear loads and to increase stability, multivariate control methods have been studied [64], [65]. Power sharing control is categorized depending on whether it uses the idea of droop control. If the central controller deals with the power sharing control, it can be classified in the secondary control [12].

P-f/Q-V droop control, also referred to as conventional droop control, is widely used at the primary control level [18], [66]-[68]. It is only effective for the large-scale power system in which the resistance of line is neglected and the impedance is only of inductive nature. However, high resistance/inductance ratio in low-voltage (LV) system network causes the coupling between active and reactive power, which is challenging for the conventional droop control. Thus, in LV systems, a modified droop control represented as *P-V/Q-f* is used instead of the conventional droop control.

The primary control can be categorized into droop-based control methods and non-droop-based or communication-based control methods. Figure 3 shows the detailed classification of the primary control. The droop-based control methods are characterized by the flexibility, redundancy, and easy implementation, but there are a few disadvantages such as the circulation of current among DG units, inaccurate power sharing, and slow transient response. Likewise, non-droop-based control methods have benefits such as good transient response, accurate power sharing, and good power quality, but these impose increased cost and complication of the communication loop. Moreover, long-distance communication decreases the opportunities for system expansion. The droop-based and non-droop-based methods are discussed in the following subsections.

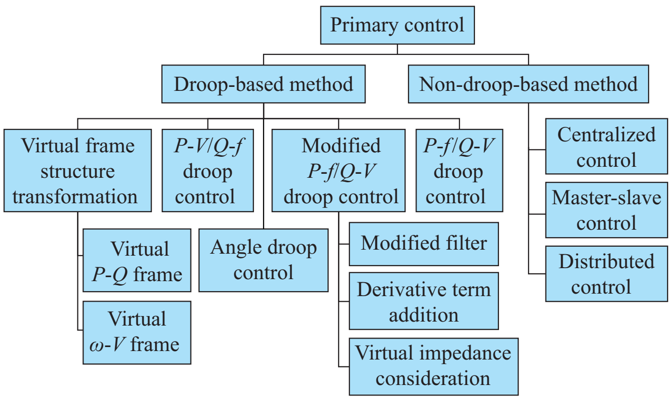

Fig. 3. Classification of primary control.

A. Non-droop-based Methods

1) Centralized Control

The centralized control involves synchronization signals and current division units, as depicted in Fig. 4.

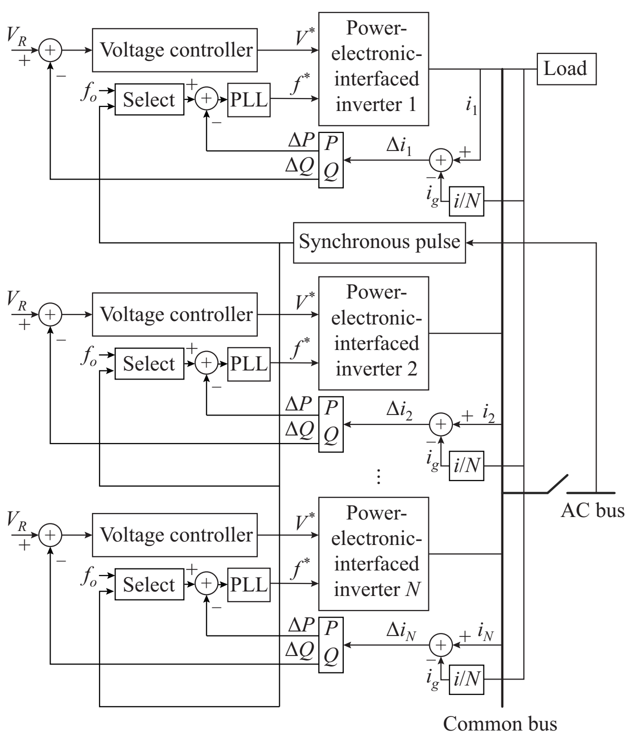

Fig. 4. Schematic of centralized control.

Each module has PLL which maintains the uniformity between the synchronization signal and the frequency and phase of the output voltage [69], [70]. The current division modules identify the total load consumption and set the reference for the current to be drawn from each module. The N DG units interfaced through the inverters of equal power rating share the current by following the expression $i_g = i_k/N$ $(k = 1, 2, \ldots, N)$, where i_k is the inverter output current. This ensures the accurate power sharing under both transient and stable conditions. Each inverter calculates the current error Δi_k by taking difference of i_k and the reference current $i_{ref} = i_g$. Since the synchronization signal ensures the insignificant change of frequency and phase between inverters, Δi_k is due to the change of their output voltages. The deviation in reactive power ΔQ and reference voltage V_R decides the set value of voltage V_g^* for the inverters. The frequent setpoint f_o and the deviation in active power ΔP determine the value of frequency f^* for the inverters.

There may be an insignificant difference in frequency and phase of the N inverters connected in parallel due to voltage imprecisions, but this error is measured and compensated by each inverter itself. This control method requires the communication of reference current and synchronization pulses for the inverters. It poses cost to the system and makes the system crucial in case of communication instabilities. The centralized controller limits the expansion of wide-area system.

The incorporation of significant electric vehicles with centralized control has been investigated [71]. The electric vehicles with centralized control have great potential in the case of islanding of the MG.

A centralized control has been investigated in [72] for improving frequency regulation in MGs with the help of plug-in hybrid electric vehicles (PHEVs) and wind generators. It is found that PHEVs and wind generators can improve frequency regulation for low-power MGs [72]. A centralized control improves the dynamic performance in case of unequal line impedances in [73].

2) Master/Slave Control

The idea of master/slave control is encouraged from a conventional power system in which the voltage and frequency are maintained by slack bus, whereas all the buses supply the load [74], [75]. Likewise, in the MG, the initializing module acts as a master inverter and maintains the conditions of paralleling the inverters, whereas others act as slave inverters which then either inject or absorb active/reactive power [15]. The master/slave control is shown in Fig. 5. The voltage regulator in the master inverter unit regulates the output voltage by tracking the reference voltage V_{ref}. The output voltage of controller V_e directs the pulse width modulation (PWM) of master inverter and is fed to slave inverters for voltage regulation. The output current of master inverter i_m is regarded as the reference current ($i_{ref} = i_m$) for all the slave inverters. The slave inverters enable equalized power sharing by tracking the reference provided by the master inverter. In such a case, it does not require any PLL signals. However, if the master inverter fails, the system is likely to fail. The improved master/slave control is studied in [75], which randomly shifts the role of the present master inverter to another inverter. An improved master/slave control in which all inverters are connected by active power sharing bus and reactive power sharing communication bus has been considered in [15]. The inverter of the highest power generation DG unit becomes the master one whereas all others are positioned to the slave status.

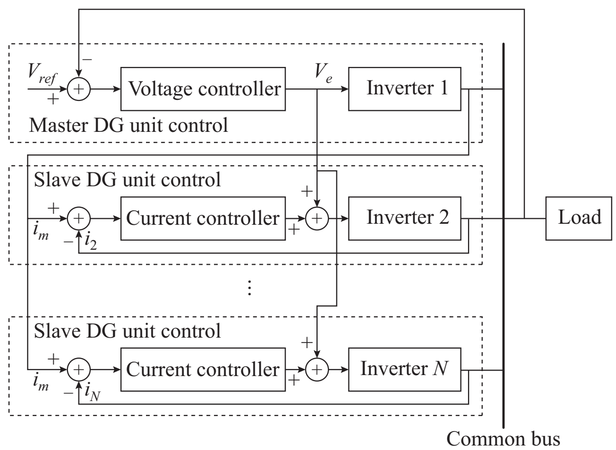

Fig. 5. Block diagram of master/slave control.

This control is easy to implement with precise power sharing, and moreover, the feature of switching the role of master inverter increases the reliability. The DG units also have "plug-and-play" characteristics for their connection and disconnection, which optimizes the efficient execution of the available potential. Nevertheless, it cannot sustain overshoot transients of output current, as the output current of master inverter is only controlled. A multi-master/slave control method is investigated in [76] for the improvement of voltage quality and frequency regulation. It shows the improved performance for the dynamic load.

3) Distributed Control

The distributed control, as shown in Fig. 6, does not use a central controller. Instead, it requires discrete control for each inverter connected in parallel [14], [77]-[81]. A distributed control is usually characterized by the instantaneous average current sharing. It requires a current sharing bus for average current sharing and synchronization of voltage reference. To ensure the same average reference current, for all the inverters connected in parallel, another current control loop is used. In case of failure in a single unit, it can be disconnected easily from the MG without interrupting the parallel operation.

As shown in Fig. 6, the current error i_{en} is split into dq components and the current regulators maintain the frequency and amplitude of the voltage. Figure 6 depicts the distributed control system. The values of output current of DGs i_{ok} ($k=1,2,...,N$) are averaged, i. e., $i_{ave}=\frac{1}{N}\sum_{k=1}^{N} i_{ok}$. The output voltage V_{o1} and current i_{o1} are fed back to be compared with the reference voltage and average current provided by current sharing bus, respectively. The current error of DG1 i_{e1} is decomposed into dq components i_{e1d}, i_{e1q}, and the current regulators maintain the frequency and voltage of DG1. Likewise, the current error of the N^{th} DG i_{eN} as comparison of i_{oN} and i_{ave} is also split into dq components i_{eNd}, i_{eNq}. The lower bandwidth communication required for distributed control as the information is exchanged in nearby units but not in system-wide area. It shares the control responsibilities among the DG units instead of dispensing control with the central controller. A malfunction of one DG unit does not affect the parallel operation of inverters in an MG. To ensure accurate reactive power sharing and to reduce frequency and amplitude deviations, a networked control system has been studied [81]. A two-layer control has been explored in [80], in which the first layer decouples the voltage and frequency, and the second layer decouples the active and reactive power. A distributed control employs partial feedback linearization for active and reactive power sharing and it also takes the known parameters into consideration [14]. Reference [82] proposes a distributed primary control using sparse communication, and achieves accurate load sharing and voltage regulation.

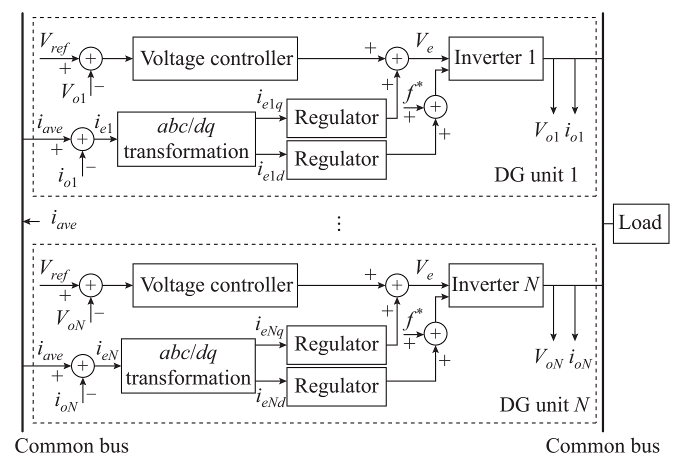

Fig. 6. Block diagram of distributed control.

Thus, the distributed control achieves better power sharing and voltage regulation without using a central controller, but the communication between DG units is necessary, which constrains the expansion of the system.

B. Droop-based Control Methods

1) P-f/Q-V Droop Control

This control initiates from the droop characteristics of synchronous generator, in which the difference between mechanical and electrical power changes the rotor speed, and consequently, the electrical frequency. Similarly, the reactive power depends on the output voltage. The relationships of active power and frequency, and reactive power and voltage can be derived by (1) and (2), respectively.

$$f_o=f^*-K_P\left(P_o-P^*\right) \tag{1}$$

$$V_o=V^*-K_Q\left(Q_o-Q^*\right) \tag{2}$$

where V_o is the measured quantities of voltage; V^* is the references for output voltage; P_o and Q_o are the measured values of active and reactive power, respectively; P^* and Q^* are the reference values of active and reactive power, respectively; and K_P and K_Q are the frequency and voltage droop coefficients, respectively, which can be determined by (3) and (4). The characteristics of conventional droop control are depicted in Fig. 7 [83]. The line P_1^* to $P_{1,\max}$ represents droop curve of DG1, where P_1^* is the minimum power drawn at rated frequency; and $P_{1,\max}$ is the maximum power drawn at minimum acceptable frequency $f_{\min}$ which demonstrates the inverse relationship of power and frequency in droop characteristics. Likewise, lines P_2^* to $P_{2,\max}$ until P_N^* to $P_{N,\max}$ are the droop characteristic curves from DG2 to the N^{th} DG. For ease of understanding, it is supposed that DG units do not provide reactive power at rated voltages in Fig. 7(b), but only active power is generated. However, $Q_{1,\max}$, $Q_{2,\max}$, and $Q_{N,\max}$ are the quantities of reactive power drawn by DG1, DG2, and the N^{th} DG at the minimum acceptable voltage $V_{\min}$, respectively.

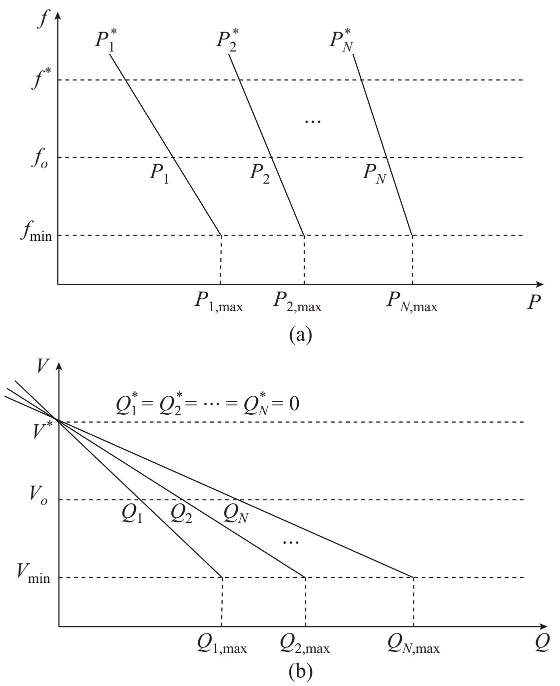

Fig. 7. Conventional droop characteristics. (a) *P-f* droop. (b) *Q-V* droop.

$$K_P = \frac{\Delta f}{P_{norm}} \tag{3}$$

$$K_Q = \frac{\Delta V}{Q_{norm}} \tag{4}$$

where Δf and ΔV are the maximum allowed deviations in angular frequency and output voltage, respectively; and P_{norm} and Q_{norm} are the nominal active and reactive power generated by the system, respectively.

The output impedance of inverters connecting the DG units to the MG is inductive because of the inductive line impedance and inductive filter in the power system. The block diagram of the droop control is shown in Fig. 8. The output currents I_o and voltages V_o of the inverter units determine the active and reactive power of DGs. The product of droop coefficients K_P, K_Q, and the power components P, Q are compared with rated frequency ω^* and voltage E^* to generate the signals of frequency ω and voltage E. Figure 9 presents the equivalent circuit and the phasor diagram of two inverter-interfaced DG units connected in parallel through a PCC. In Fig. 9, $R_1+\mathrm{j}X_1$ and $R_2+\mathrm{j}X_2$ are the output impedances of the inverter 1 and inverter 2, respectively; $Z_{L1}=R_{L1}+\mathrm{j}X_{L1}$ and $Z_{L2}=R_{L2}+jX_{L2}$ are the impedances of line 1 and line 2, respectively; $E_1\angle\alpha_1$ and $E_2\angle\alpha_2$ are the voltages of two inverters, respectively; Z_{load} is the load impedance; V is the common bus voltage; X is the inverter output reactance; and I and α are the inverter current and phase angle difference between two voltage values of inverter 1 and inverter 2, respectively. If the system is large and has inductive impedance, the active and reactive output power can be represented by the following equations.

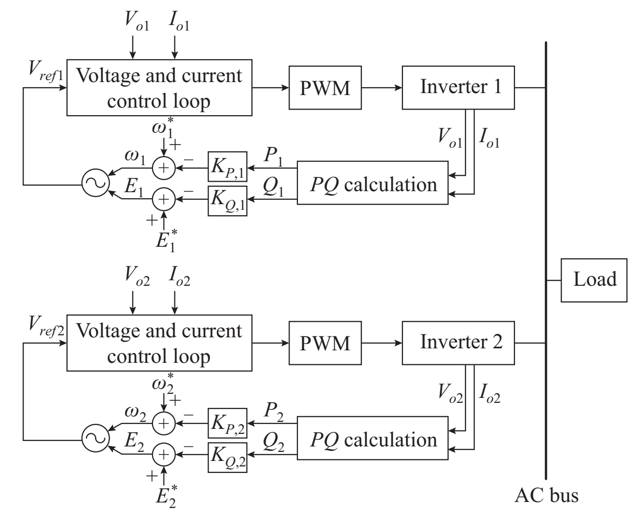

Fig. 8. Block diagram of conventional droop control.

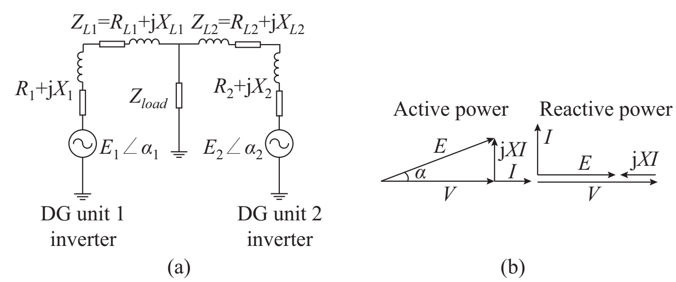

Fig. 9. Diagram of two DG units connected in parallel through inverters. (a) Equivalent circuit. (b) Phasor diagram.

$$P = \frac{EV\sin\alpha}{X} \tag{5}$$

$$Q = \frac{EV\cos\alpha - V^2}{X} \tag{6}$$

From (5) and (6), it can be seen that the active power of the inverter mainly depends on the power angle, and reactive power depends on the difference between E and V.

The inverters connected in parallel in MG also consider the frequency droop coefficient and voltage droop coefficient to regulate the output of the inverters.

2) Modified P-f/Q-V Droop Control

The limitations of droop control lie particularly in power sharing under uncertain output impedances and dynamic load conditions due to active and reactive power coupling and the presence of circulating current among DG units. These conditions limit the sharing of harmonics between DG units and result in poor transient response. Such issues have been considered, and several methods have been proposed to solve them. One of the proposed methods is an improved *P*-

f/Q-V droop control [84] which adjusts the output impedance with the help of virtual impedance. The virtual impedance does not cause any losses such as those due to real impedances, and it is implemented by a control loop. Thus, it improves the efficiency and stability of droop control. A modified droop control presented in [45] suggests that accurate power sharing and frequency restoration can be achieved through the virtual inertia offered by the low-pass filter. It also considers virtual damping to overcome the lingering frequency deviations leftover by the applied control. An improved Q-$\dot{V}$ droop control is proposed, which uses first-order derivative of reactive power of inverter and maintain the required reactive power [85]. This control remains stable under the acceptable limit of droop coefficients. However, a further increment of voltage droop coefficient could lead to instability.

1) Modified filter

All the DG units are connected to the MG through the inverter and low-pass filter, as shown in the block diagram of droop control in Fig. 10. In order to provide the average values of power $\overline{P}$ and $\overline{Q}$ to the control loop, the instantaneous values of power are converted to the average ones when passed through low-pass filter. The transfer function of the filter $F(s)$ can be expressed by (7), and the change in the design of the filter provides opportunities for improving the power quality. Some researchers have improved the filter design [61], and their transfer function is given in (8).

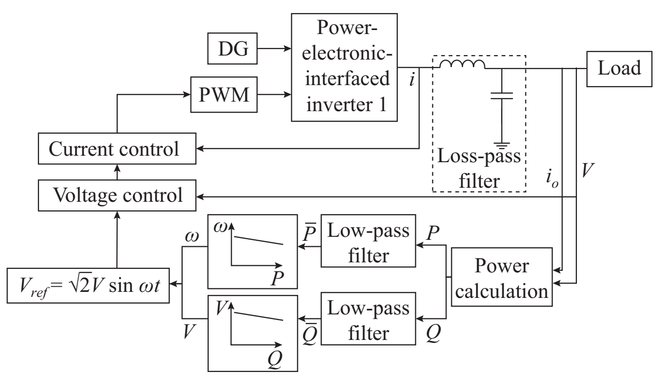

Fig. 10. Conventional droop control system.

$$F(s)=\frac{\omega_c}{s+\omega_c} \tag{7}$$

$$F(s)=\frac{\omega_c}{s+\omega_c}\frac{s^2+2\zeta_1\omega_n s+\omega_n^2}{s^2+2\zeta_2\omega_n s+\omega_n^2} \tag{8}$$

where ω_c is the cut-off frequency of low-pass filter; ω_n is the nominal frequency set-points; and ζ_1 and ζ_2 are the notch parameters of the improved design of filter. This design enhances the Q factor of the filter and enables the active and reactive power to be ripple-free by adjusting the values of ζ_1 and ζ_2. Before such design, a complete knowledge of system variables and their permissible limit parameters are required. The proposed filter improves the power quality of active and reactive power, and eliminates the ripple from active and reactive power. The proposed method improves the transient response, but other issues such as the precise power sharing and harmonics due to non-linear load still persist.

2) Adding derivative terms

The dynamic response of DG control in the presence of varying load can be improved by adding derivative terms in the droop control equations [63]. The new equations of modified droop are expressed as:

$$\omega=\omega_{ref}-K_P P-\hat{c}_p\frac{\mathrm{d}P}{\mathrm{d}t} \tag{9}$$

$$V=V_{ref}-K_Q Q-\hat{c}_q\frac{\mathrm{d}Q}{\mathrm{d}t} \tag{10}$$

where $\hat{c}_p$ and $\hat{c}_q$ are the coefficients which improve the transient response; and V_{ref} and ω_{ref} are the reference voltage and frequency for the inverter, respectively. The additive terms are valid only for system dynamics, not under steady-state condition. It improves the response speed of conventional control when the load changes. The derivative term is added with conventional droop control which eliminates the power oscillations.

3) Consideration of virtual impedance

In case of mismatched line impedance, the DG units connected in parallel through inverters are not capable of managing desirable reactive power sharing among them. Consequently, the balanced active and reactive power sharing is affected which may lead to system failure. It requires the decoupling of active and reactive power to achieve accurate power sharing and to avoid the circulation of current among MGs. Significant research has been conducted to incorporate virtual impedance to solve the above-mentioned issues [41]. This method includes the virtual impedance in the fast control loop of the droop control which imitates the line impedance. Thus, V_{ref} can be expressed as:

$$V_{ref}=V^*-Z_v I_o \tag{11}$$

where Z_v is the virtual output impedance; and V^* is the output reference voltage.

The block diagram of the virtual impedance is shown in Fig. 11. Z_v is intended to supersede the line impedance Z_l, i.e., $Z_v>Z_l$, and its phasor diagram is shown in Fig. 12. As shown in phasor diagram in Fig. 12(b), the DG output voltage E creates a phase angle α with system voltage. $R_v\bar{I}$ and $X_v\bar{I}$ are the voltage drops due to the virtual resistance R_v and virtual reactance X_v, respectively. $R_l\bar{I}$ and $X_l\bar{I}$ are the voltage drops due to line resistance and line reactance, respectively. The system is connected to the utility at the PCC with voltage V_{PCC} and phase angle ϕ. $\bar{I}$ is the inverter current that makes an angle θ with V_{PCC}. If the voltage drops across each inverter V_{drop1} and V_{drop2} are considered equal to achieve stable reactive power sharing, the summation method can be applied to determine the virtual impedance.

$$V_{drop1}=\left(Z_{l1}+Z_{v1}\right)I_{l1}=V_{drop2}=\left(Z_{l2}+Z_{v2}\right)I_{l2} \tag{12}$$

where Z_{v1} and Z_{v2} are the virtual impedances of the inverters 1 and 2, respectively; and Z_{l1}, Z_{l2}, I_{l1}, and I_{l2} are the line impedances and currents of inverters 1 and 2, respectively.

In the above-mentioned summation method, the virtual output impedance of one inverter is fixed to be zero, and the virtual output impedance of the other inverter is set to imitate the line impedance.

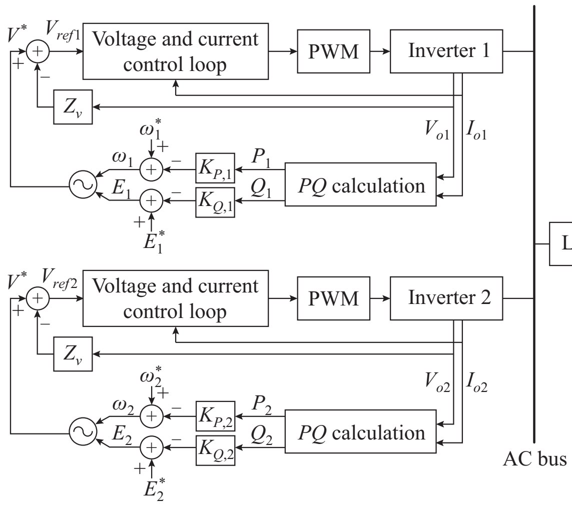

Fig. 11. Block diagram of virtual impedance droop control.

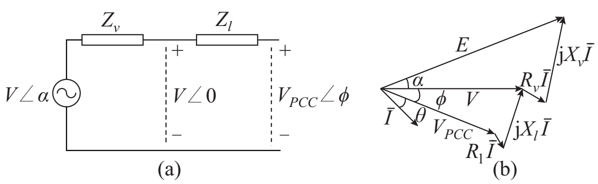

Fig. 12. Equivalent model and phasor diagram of virtual impedance droop control. (a) Equivalent model. (b) Phasor diagram.

Taking $Z_{l1} > Z_{l2}$, we may achieve $Z_{v1} = 0$ from (12). Then, (12) can be expressed as:

$$Z_{v2} = Z_{l1} - Z_{l2} \tag{13}$$

This summation may reduce the virtual output impedance, which, in turn, improves the voltage regulation. It also enhances the sharing of reactive power if the output voltage is significantly higher than the voltage drop of the line.

A control method using improved droop technique based on coupling compensation is presented in [86], which improves dynamic performance and reactive power control. By using virtual impedance for decoupling the power, the proposed control method achieves more performance improvement in particle swarm optimization. An improved virtual impedance control method has been proposed in [56] to achieve enhanced reactive power and harmonic sharing among DG units at the standard operation frequency and designated harmonic frequencies. The droop control that uses enhanced virtual impedance is depicted in Fig. 13, where $I_{inv,\alpha}$ and $I_{line,\alpha}$ are the components of inverter current and line current, respectively. Two voltage regulation loops are implemented including virtual fundamental reference voltage regulation and virtual harmonic voltage regulation. The reference voltage $V_{droop,\alpha}$, $V_{droop,\beta}$ and $\alpha\beta$ components of unfiltered line current are used to compute the average power. Similarly, the $\alpha\beta$ components of voltage at PCC $V_{PCC,\alpha}$, $V_{PCC,\beta}$ after transform from dq components $V_{PCC,d}$, $V_{PCC,q}$ are used to determine the virtual harmonic voltage V_{vh}. The output of fundamental reference voltage is obtained after the deduction of voltage at line capacitor $V_{c,\alpha}$ and V_{vh}. The outputs of both loops are passed via a low-pass filter to determine I_{ref}. Besides, K_{pi}, K_{if}, K_{ih} are the proportional gain, resonant gain of fundamental voltage loop, and resonant gain of virtual harmonic impedance loop, respectively; K_i is the proportional gain of inner loop; and V_{vf} is the virtual fundamental voltage. It reduces the computation work of the DG local controller by excluding the need of fundamental and harmonic components. Furthermore, it minimizes the equivalent harmonic impedance of DG unit, and thereby, alleviates harmonic voltages at PCC. However, it needs the data of line impedance parameters and low-bandwidth communications.

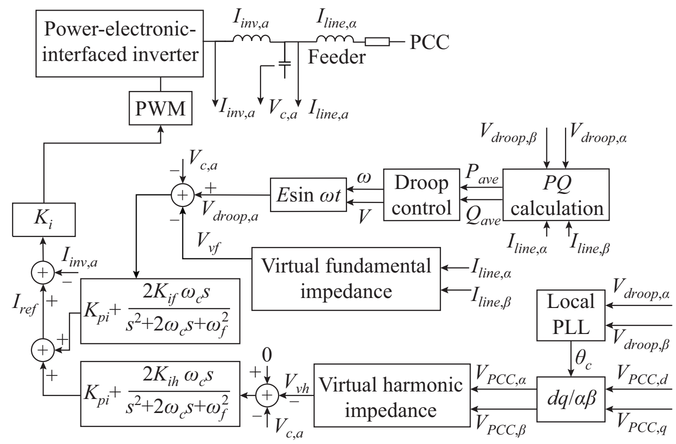

Fig. 13. Droop control with enhanced virtual impedance.

3) P-V/Q-f Droop Control

The ratio of reactance X to resistance R is very low in low-voltage networks, i.e., the inductance is negligible compared with the resistance. In most cases, this R/X ratio is approximately 7.7. Thus, (7) and (8) are invalid under this condition, and the expressions in (14) and (15) become valid.

$$\delta \cong -\frac{RQ}{V_1 V_2} \tag{14}$$

$$V_1 - V_2 \cong -\frac{RP}{V_1} \tag{15}$$

where δ is the power angle. It can be interpreted from these expressions that the power angle depends on reactive power consumed, and the voltage difference relies on the active power. Thus, the voltage can be regulated by controlling active power, and the frequency can be maintained by controlling reactive power. Thus, the following equations represent the *P-V/Q-f* droop control.

$$\omega = \omega_{ref} + K_Q Q \tag{16}$$

$$V = V_{ref} + K_P P \tag{17}$$

It is noted that this method cannot be applied to the distribution system with medium-voltage lines, as the impedance parameters change significantly compared with those of low-voltage networks. Then, (14) and (15) will not remain valid as the active power depends on not only the difference of voltage or power angle, but also the reactive power. Both active and reactive power are inter-related and cannot be controlled individually through power angle or voltage difference.

4) Angle Droop Control

This method is influenced by the conventional *P-f/Q-V* droop control. In this control method, the voltage angle drops with active power. The frequency variation with angle droop control is much less than the conventional *P-f/Q-V* droop controller. Figure 14 represents the block diagram of the angle droop control, where P_b^* and Q_b^* are the references of active power and reactive power, respectively; P_b and Q_b are the instantaneous active and reactive power, respectively; and δ_P^* and δ_P are the reference angle and instantaneous angle, respectively. The limitation is that it necessitates GPS signals for synchronizing the reference signal [25], [43].

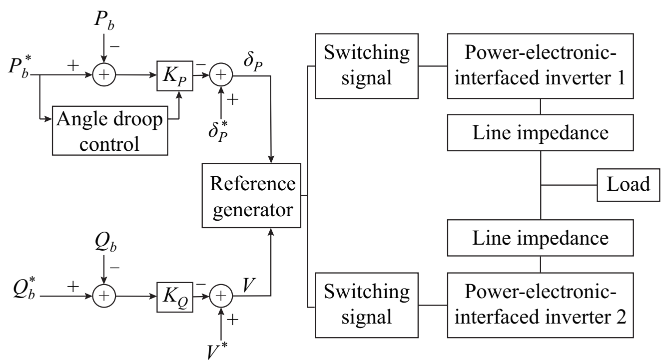

Fig. 14. Block diagram of angle droop control.

A modified angle droop control is presented in [36], in which only the medium-voltage lines are considered. It uses a decoupling method and achieves more significant improvement in power sharing than conventional angle droop control. A phasor measurement unit (PMU) based on angle droop control is presented in [87], which achieves precise power sharing.

5) MG Control Based on Virtual Frame Structure Transformation

1) Virtual *P-Q* frame

The virtual *P-Q* transformation method is used to decouple active and reactive power to ensure accurate sharing control [49]. Typically, the impedance of the line with both resistance and reactance is considered, and the active and reactive power is expressed as:

$$P_i \cong \frac{V}{Z}\left[\left(E_i - V\right)\cos\theta + E_{i\phi}\sin\theta\right] \tag{18}$$

$$Q_i \cong \frac{V}{Z}\left[\left(E_i - V\right)\sin\theta + E_{i\phi}\cos\theta\right] \tag{19}$$

where Z is the magnitude of impedance. There is a coupling between active and reactive power, as can be observed from the above expressions. Thus, the active and reactive power is transformed into a virtual frame using an orthogonal rotational transformation matrix $\boldsymbol{T}_{PQ}$ as follows.

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} = \boldsymbol{T}_{PQ} \begin{bmatrix} P \\ Q \end{bmatrix} \tag{20}$$

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = \begin{bmatrix} \dfrac{X}{Z} & -\dfrac{R}{Z} \\ \dfrac{R}{Z} & \dfrac{X}{Z} \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} \tag{21}$$

Although the line impedance is mixed, the decoupling of *P/Q* can be achieved for inductive networks. After the transformation of active and reactive power to P' and Q', no coupling exists between them. It is useful to decouple the P and Q, but in the case of DG units with unity power factor, both P' and Q' are required to be controlled. However, only frequency control would be enough if *P-f/Q-V* control is applied, as the voltage is maintained to keep $Q=0$ from such DG units.

2) Virtual ω-V frame

Like *P-Q* frame transformation, the virtual frequency/voltage frame ω'-V' can be expressed as:

$$\begin{bmatrix} \omega' \\ V' \end{bmatrix} = \begin{bmatrix} \sin\theta & \cos\theta \\ -\cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} \omega \\ V \end{bmatrix} = \boldsymbol{T}_{PQ} \begin{bmatrix} \omega \\ V \end{bmatrix} \tag{22}$$

$$\begin{bmatrix} \omega' \\ V' \end{bmatrix} = \begin{bmatrix} \dfrac{X}{Z} & \dfrac{R}{Z} \\ -\dfrac{R}{Z} & \dfrac{X}{Z} \end{bmatrix} \begin{bmatrix} \omega \\ V \end{bmatrix} \tag{23}$$

The values of ω and V are determined using conventional droop control, and then, the transformed frequency and voltage (ω' and V') are used to set the reference for the control of DG units. This control can ensure the complete decoupling of active and reactive power. However, if the virtual transformation angle of the individual DG units is different, the transformed values of frequency and voltage will also be different in respective virtual frames of DG units. As a result, it will lead to mismatched impedances and different references for DG units, and the synchronism of the inverter may be lost. Figure 15 presents the ω'-V' virtual frame transformation [49]. It shows that the transformed frame ω'-V' should be bounded within the limits of the initial frame ω-V described by the rectangle (a', b', c', and d'). This reperesents the permissible change of voltage $\Delta V'$ and frequency $\Delta\omega'$ in the original frame. The voltage will remain between V^* and $V_{\min}$, and the frequency will be restricted between ω^* and $\omega_{\min}$.

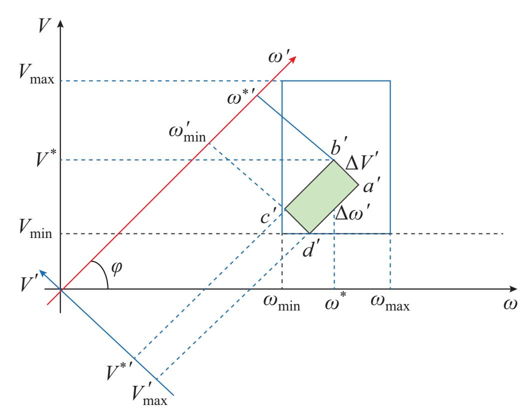

Fig. 15. ω'-V' virtual frame transformation.

C. MG Control Based on Virtual Synchronization Machine (VSM)

In a conventional power system, synchronous generators play a vital role in dealing with a variable short-term peak demand of the load with available inertia of the interconnected power system. However, DG units based on renewable sources lack this characteristic, and this poses a reliability issue. Both the VSM and the droop control are based on the concept of synchronous generator emulation [88]. The difference between them is that VSM has virtual inertia by applying the swing equation, while the droop control only manages active and reactive power [89]. In islanded MGs, this issue becomes very sensitive for critical loads. In [90]-[92], a control method based on VSM is proposed. The VSM may involve DS, control algorithm, and inverter as shown in Fig. 16 [93]. It replicates the operation characteristics of a synchronous generator and provides virtual inertia to regulate the voltage and frequency stability [93], [94]. A p-ω control is presented in [95] to emulate the swing equation characteristic of the synchronous generator, which improves the dynamic performance more than the conventional control.

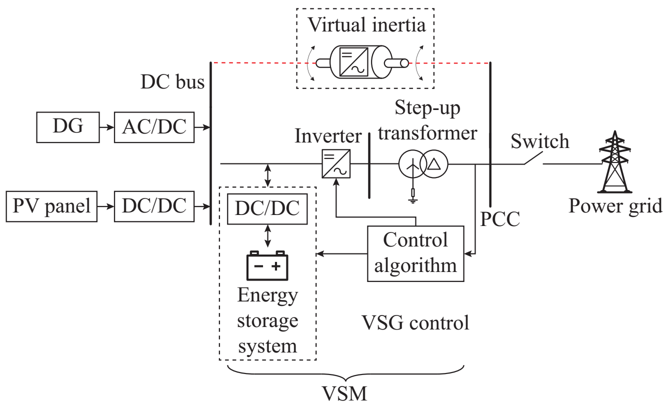

Fig. 16. VSM-based control.

Apart from the inertia, the transients due to power sharing are controlled by VSM. Due to its promising control performance, VSM has been investigated for doubly-fed induction generator and modular multilevel converter (MMC) [96], [97]. VSM uses DS for frequency control by governing the amplitude, power flow, and rate of change of frequency [92].

V. Secondary Control

The secondary control is responsible for reliable and economical operations of MGs. Therefore, it is functionally referred to as MG EMS. Two core methods can be acknowledged in this area: decentralized and centralized. Decentralized control helps interact with various units of MG for facilitating a distributed decision-making process, whereas centralized control commonly depends on the operation of the central controller.

The centralized control allows an implementation of the continuously updated optimization where the complete data are collected at one point. However, it does not offer the desired plug-and-play feature. On the other side, the decentralized control integrates new DG units without making the continuous variations to controller setting, but there exists complications in the handling operations of MGs, which require an advanced management level.

Generally, centralized control is suitable for remote MGs with rigid structure and those with critical demand-supply, whereas the decentralized control is suitable for grid-connected MGs with several owners and a variable number of DG units.

A. Centralized Secondary Control

The frequency and voltage of each DG unit are measured in the centralized control and compared with the reference values provided by the grid-connected network. The primary control receives the error between the reference and actual values and then reinstates the voltage and frequency. The secondary control for the restoration of voltage and frequency has been investigated in [98]-[100]. The centralized secondary control is considered in [81], which aims to manage harmonics and voltage deviation. In the case of MG with unequal feeder impedances for voltage restoration, the negative sequence current cannot be distributed among DGs. This issue may be addressed by a dynamic consensus algorithm (DCA) using distributed finite-time control to converge DG parameters into reference values in the predetermined time. Thus, the frequency and voltage are decoupled, and consensus-based frequency control is used to restore the frequency.

Automatic generation control is established by the centralized control to recall and overcome the deviations in the frequency and voltage of the MG [101]. Its structure contains the available information of DG units, the load of central controller of the MG, and network load, e.g., technical limitations/characteristics, economizations, operation modes, and network parameters, etc., together with the information from the forecasting system, e.g., solar irradiance, local load, and wind speed, for determining a suitable unit commitment (UC) and dispatching of resources according to the designated objectives.

Decisions can be made by the central controller by using either the online calculation of optimum (or near optimum) action or pre-defined online database with the information of appropriate operation conditions from offline controls or other experiential methods. The real use of centralized control is covered in detail in [102]. The block diagram of the centralized secondary control is represented in Fig. 17, where δ_f is the frequency compensation due to the frequency error, which is communicated to the local controller to maintain the frequency of DG units.

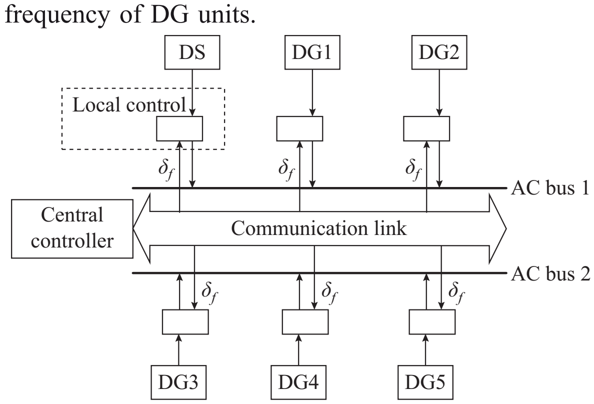

Fig. 17. Block diagram of centralized secondary control.

The offline calculations of optimized operations for all probable scenarios may be the best substitute in terms of the performance and cost of the system in small MGs with lower power generation profiles [83]. In the method presented in [103], all the possible operation states are analyzed offline, and in each case, the optimal dispatching of the system is figured and saved in a look-up table to be analyzed in real-time operations. A similar type of method is shown in [104].

To select a suitable system operation in centralized secondary control, the data of cost function and operation limits of DG units are conveyed to the central controller of the MG [83]. The data of operation limits and cost functions of the DG units are transmitted to the central controller of the MG to determine the most suitable operations in centralized secondary control. It is more efficient to allow the customers and DGs to propose their power consumption and power generation, respectively, rather than just incorporating the availability and cost functions [105].

The optimization of MG operation can rely on the utilization of DS on a long-term basis. Moreover, when there is surplus or shortage of power, the DS can help maximize the output of dispatchable DG units and provide an economized operation during peak hours, which, therefore, saves the MG to deploy new DG units [83].

Due to the presence of long-term DS, multi-level dispatching methods are proposed for accommodating storage resources properly [106] - [109]. With variable DG units and DS, the commitment decisions of DG units in the MG for day-ahead are discussed in detail in [106]. The decision for UC is executed continually with an interval of fifteen minutes to ensure the dispatching of DG units to be close to their programmed contributions, and to have a voltage level within the permissible limits. Another method for the MG with wind-turbine and hydrogen-based DS has been investigated in [107].

B. Decentralized Secondary Control

The position of the central controller decides whether the control is decentralized or centralized. In decentralized control, the measurement of voltage and frequency is done at the communication link. Later, the measured values and errors are fed to the primary control [81]. Figure 18 represents the decentralized secondary control.

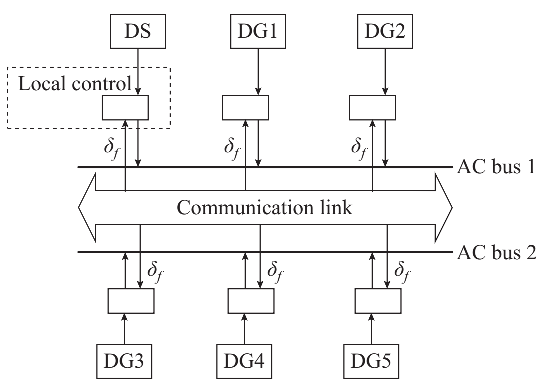

Fig. 18. Block diagram of decentralized secondary control.

When the droop control is applied to the MG with inductive nature, it experiences inaccurate power sharing. Thus, the voltage and frequency remain unstable. Many techniques have been proposed using primary control, but result in small inaccuracy in power sharing. A distributed secondary control (DSC) can restore the fundamental values of frequency and voltage. DSC is not based on an MG central controller (MGCC). Thus, there are fewer chances of complete system loss in case of the failure of central controller. Reference [110] proposes a decentralized secondary control to achieve power sharing in a droop-controlled MG. To restore frequency and achieve precise power sharing, a decentralized control has been studied in [111]. For synchronization, it uses the detection of load change moments in each DG unit instead of communication, and achieves satisfactory performance. A DSC for voltage deviation compensation is proposed which permits the communication among local DGs to utilize the global information [112].

The issues of energy management are also solved by DSC of the MG, providing the maximum-possible self-sufficiency of different DG units. Though decentralized control can utilize the hierarchical structure for the exchange of data, the decision for control variables is made locally. The autonomy is accomplished through the hierarchical structure with at least three levels, i. e., local controllers (LCs), MGCC, and distribution network operator (DNO) [105]. The DNO lies in the tertiary control category, which interrelates the MG with neighboring MGs. The MGCC directs the accumulated operations of the loads and DGs within MG, and is accountable for their economic and reliable operations and interaction with the main grid. Moreover, LCs control DGs within the MG or the aggregation of DGs, which interact with the upper-level controllers and try to attain global and local intents. In the decentralized architectures, LCs interact with other LCs and MGCC for sharing information, requesting/offering service, communicating prospects, and exchanging any extra information related to MG operations.

The decentralized secondary control systems are mainly dealt by MAS in literature. MAS is a system composed of several intelligent mediators by providing local information, which interacts with each other to attain various local and global objectives. It is expected that multiple factors including the connectivity, functionalities as well as the responsibilities of individual agents, and the information that the agents can share, are essential for the performance of the system [113]. The agents are the objects that take the situation into consideration and can communicate some levels of self-sufficiency depending on their individual objectives and inadequate information of an environment, i. e., terminal measurement [114].

The MAS-based DSC for the MG is initially reported in [115], as a substitute for coordinated operations of the MG in the competitive market environments with numerous generator owners. The relevant factors of MG are assembled and denoted by various agents that relate in the market environment for determining MG operations. In this way, the consumers, main grid, generators, and DS system contribute in the market by transmitting the information of buying/selling energy to MGCC depending on their specific requirements, accessibility, price functions, technical restrictions, prospects, and predictions. The MGCC handles the settlement of the MG market to match the selling/buying bids for increasing the social welfares, and confirms the viability of subsequent dispatching. A similar type of MAS method has been proposed in [116], in which the power flow calculation is done to verify that the dispatching attained in the market fulfills the technical criteria and other functioning limits. An MAS-based architecture is introduced in [117], which includes more agents that allow the scheduling of the multi-stage operation of the MG. Service agents offer the forecasting information and database service to LCs for improved energy resources management over extended operation horizons. However, special procedures and protocols need to be studied for properly handling the information to achieve the desired feature.

VI. Critical Discussion on MG Control

The conventional droop control has a limitation when the feeder impedance in the MG is inductive, i.e., the resistance is negligible [118] - [120]. Likewise, the secondary control has limitations when the feeder impedance is not matched between DG units, and it causes poor reactive power sharing [121]. The active power sharing can be possible by selecting the rational droop coefficient. Increasing the value of the droop coefficient may improve the active and reactive power sharing, but it causes the high-voltage variations from the standard values [122] - [124]. When the feeder impedance is resistive which causes the coupling between the active and reactive power, the active power sharing is consequently compromised. Also, applying conventional secondary control to MG improves voltage regulation but compromises over-reactive power sharing [34]. The dynamic stability of the control is affected when there is an MG changeover from islanded to grid-connected mode and vice versa. There are modified droop control methods proposed in [50], [125]-[127]. To improve the performance of conventional droop control, [128] proposes a partial transient power coupling method by modifying the frequency droop control. Besides, power sharing, voltage, and frequency stability are also crucial, and thus, the above-mentioned issues may be considered while adapting the droop control to achieve accurate active power sharing.

The incorporation of RES-based DG units causes poor power sharing due to their variable characteristics. Even though the maximum power point tracker can help extract active power, it poses the stability issues in the MG [129]. The centralized control and secondary control are combined to achieve reactive power sharing and voltage regulation. This combination uses communication partly, thereby reducing its cost. However, the capacity of reactive power and communication time delay have not been considered [130]. This control is useful as the value of reactive power is taken directly and remains unaffected by the load impedance, and can sustain unbalanced and non-linear loads. However, the two-layer control adds complexity in the MG control. The communication helps the control system determine the power value, but may introduce a delay that can cause power loss in the MG. The communication delay has not been considered in the control methods and its implementation may require further consideration.

VII. Future Trends

MGs have tremendous potential to transform the conventional power system to solve its present challenges. However, to encourage the worldwide implementation of MGs, a few areas need improvement.

Linear loads have been considered in several investigations [131], [132], but non-linear loads, i. e., electric vehicles, induction motors, etc., have not been studied precisely. Advanced control methods are required which can handle the non-linear loads. It necessitates the determination of stability limitations of DGs while applying the practical scenarios with the variable nature of loads.

A critical aspect for DGs is the power sharing among them. Control methods have been applied to ensure the desired active and reactive power sharing. However, reactive power sharing, in the case of nonlinear loads, is still a challenge for future research [11], [41], [133]. Besides power sharing, power quality issues such as harmonics, power factor, voltage stability are the crucial aspects to be considered.

It has become easier these days to test the MGs considering the practical situation with the help of real-time simulators. These simulators help emulate the various parts of the MG and make it easier to test any hardware devices connected to it. More practical implementations in grid-connected mode will create more opportunities for the expansion of the MG.

Communication has been widely used in many control methods of the MG to increase the efficiency of the system, but it also poses challenges. The communication time delay can drastically decrease the efficiency of the system and lead to failure. Also, communication may be exposed to cyber-attacks. More research on communication delay and its security issues can increase the reliability of MGs.

Since the protection in the conventional power system has standard operation mechanism, the integration of MGs on the utility scale will require changes in the coordinated protection of the overall system. There is a bidirectional power flow in grid-connected MGs, which necessities the changes in the protection schemes of the system.

VIII. Conclusion

This paper presents a comprehensive review of the primary and secondary control methods for the hierarchical control of the MG. It is conferred in the literature that from droop-based control techniques, the modified droop control with virtual impedance and virtual frame structure transformation can overcome the shortcomings of the conventional droop control. These cater to the issues of the feeder impedance mismatch between DG units that result in poor active and reactive power sharing, and frequency and voltage instabilities in the MG. However, to solve the above-mentioned issues, the non-droop-based control methods have been helpful but add extra cost and complexity due to the communication. The secondary control determines the references of active and reactive power output from the DG units connected in the MG. Two methods in the secondary control are applied to ensure the economical and reliable operation of the

MG, i.e., centralized and decentralized. The centralized method collects all DG units data and defines the system parameters based on central controller decisions. Since it continuously monitors the data and does not offer the plug-and-play characteristics for new DG units, it is appropriate for application in remote MGs. Meanwhile, the decentralized method can handle the addition and disconnection of the DG units, and therefore, it suits the grid-connected MGs. Finally, the current challenges and future trends in the implementation and expansion of the MG have been discussed to highlight the perspectives of future research.

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Kafeel Ahmed received the B.E. and M.Eng. degrees in electrical engineering from the Mehran University of Engineering and Technology, Jamshoro, Pakistan, and the University of Malaya, Kuala Lumpur, Malaysia, in 2010 and 2016, respectively. He is currently pursuing the Ph. D. degree in the School of Software and Electrical Engineering, Swinburne University of Technology, Melbourne, Australia. Prior to his doctoral studies, he was a Senior Lecturer at DHA Suffa University, Karachi, Pakistan. His research interests include renewable energy systems, microgrid systems, wireless power transfer, and power conversion.

Mehdi Seyedmahmoudian received the B.Sc., M.Eng., and Ph.D. degrees in electrical engineering in 2009, 2012, and 2017, repectively. He is currently a Senior Lecturer with the School of Software and Electrical Engineering, Swinburne University of Technology, Melbourne, Australia. Prior to his current position, he was a Lecturer and a Course Coordinator with the School of Engineering, Deakin University, Geelong, Australia. His research interests include renewable energy systems, smart grids and microgrid systems, and the application of emerging technologies in green renewable energy development.

Saad Mekhilef received the B. Eng. degree in electrical engineering from the University of Setif, Setif, Algeria, in 1995, and the Master's degree in engineering science and the Ph.D. degree in electrical engineering from the University of Malaya, Kuala Lumpur, Malaysia, in 1998 and 2003, respectively. He is currently a Professor and the Director of the Power Electronics and Renewable Energy Research Laboratory, Department of Electrical Engineering, University of Malaya. He is also the Dean of the Faculty of Engineering, University of Malaya. He is also a Distinguished Adjunct Professor with the Faculty of Science, Engineering and Technology, School of Software and Electrical Engineering, Swinburne University of Technology, Melbourne, Australia. His current research interests include power converter topologies, control of power converters, renewable energy, and energy efficiency.

N. M. Mubarak received the B. Eng. degree in chemical engineering with academic distinction (First-class Honours) from Sri Dharmasthala Manjunatheshwara College of Engineering and Technology, VTU University, Mysore, India, in 2005, the Master's degree in biochemical engineering specialized in nanotechnology from International Islamic University, Kuala Lumpur, Malaysia, in 2010, and the Ph.D. degree in chemical engineering from the University of Malaya, Kuala Lumpur, Malaysia, in 2015. He is currently an Associate Professor in the Department of Chemical Engineering at Curtin University of Technology, Sarawak, Malaysia. His current research interests include synthesis of nanomaterial using microwave technology, synthesis of biofuel, separation process and thermodynamic and advanced material and reaction engineering.

Alex Stojcevski received the Bachelor's degree in electrical engineering and the Master's by research degree in electrical and electronics engineering, in 1998 and and 2001, respectively. He has received the Master's degree in education and the Master's degree in project based learning (PBL) in engineering and science from Aalborg University, Aalborg, Denmark, in 2007 and 2008, respectively, and the Ph.D. degree in 2004. He is currently the Dean of the School of Software and Electrical Engineering, Swinburne University of Technology, Melbourne, Australia. His research interests include renewable energy and microgrid design.