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Communication-less Primary and Secondary Control in Inverter-Interfaced AC Microgrid: An Overview

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***Abstract*—Inverters in Microgrids (MGs) face significant challenges during their parallel operations; such as accurate power sharing, deviations in system voltage magnitude and frequency, imbalance between generation and load demand. To solve these techno-economic challenges, hierarchical control structures are implemented in MGs. The structure consists of three layers as primary, secondary and tertiary controls. The control approach can be either communication-based or communication-less at the various layers. The use of communication at primary and secondary layers faces problems like communication latency, data drop-up, and expense issues. On the other hand, improved decentralized control techniques being communication-less can avoid the disadvantages of using communication. This paper presents an insight into the limitations with the communication-based approach by briefing about the centralized and distributed control techniques at the secondary control layer. Subsequently, the communication-less control techniques and algorithms to achieve accurate power sharing along with restoration of MG voltage and frequency are described. A comparison among different decentralized droop-based power sharing methods in the primary control layer are done based on review and simulations. In addition to that, improved communication-less secondary restoration techniques are explained. Finally, future research directions in these areas are listed, aiming to improve the reviewed techniques.**

***Keywords*—communication-less control, decentralized control, droop control, primary control, secondary control, voltage and frequency restoration.**

I. Introduction

By the increasing energy demand, the traditional power transmission networks are exposed to challenges by supplying electricity efficiently. Small-scale grids, i.e. microgrids (MGs) are proven technologies to be a viable alternative than modifying the existing networks as the generators, supply the load directly without passing through a long transmission line [2, 3]. Green power generation systems are accelerated with the deployment of various dispatchable/non-dispatchable distributed renewables termed as Distributed Energy Sources (DER) into MG. Different control techniques, power electronic interfaces, and their communication abilities enable the integration and operation of DER in order to operate both in islanded and grid-connected modes [4]. Based on the type of operation (either islanded or grid connected), the interfacing inverters can be classified as grid-forming or grid-following [5]. The grid-forming inverters have the capability to start the MG by setting the voltage magnitude and frequency set points. On the other hand during grid-following (also called grid supporting) mode, they synchronize with the voltage and frequency set points of the existing utility grid. The non-dispatchable DERs like solar and wind are interfaced with the grid-following inverters. On the other hand, the dispatchable units such as energy storage systems, diesel generator can be interfaced with grid- forming inverters to run the MG in the absence of the main grid.

Parallel operation of both types of inverters discussed above is required as it lowers the ripple content in the current and increases the power quality with minimum maintenance [6]. In parallel operation, converters have to share the current properly in order to avoid any circulating current among themselves. Moreover, the voltage should be regulated during active load sharing, and the synchronization should be done in terms of frequency, amplitude, and phase [7]. The architecture of a typical MG system is shown in Fig. 1 [8]. It consists of various DERs (PV, wind, ESS), equipped with local loads and global loads. The loads are apartment and building loads, which may contain both linear and non-linear loads. The low voltage (LV) bus is maintained at 400 V, which can be connected or disconnected from the medium voltage (MV) bus maintained at 20 MV using the breaker. The voltage is stepped down using the transformer as shown in Fig. 1.

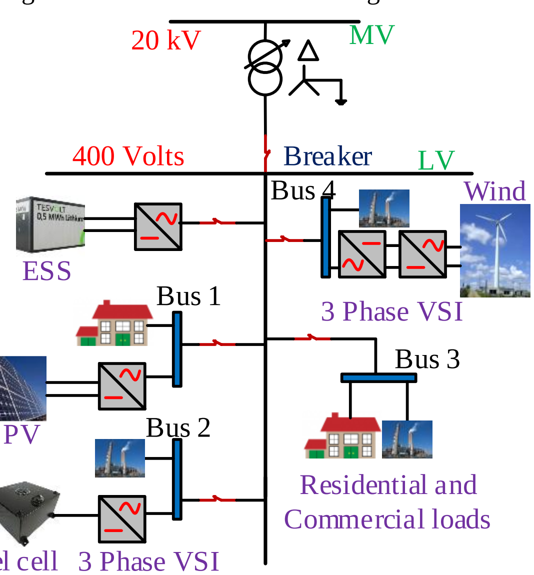

Fig. 1. CIGRE low voltage MG benchmark model [8].

Although MG can operate in both grid-connected and

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islanded modes, it has less inertia compared to the conventional power system, which makes the grid weaker [7]. Especially, in islanded mode of operation, scenarios like the intermittency of renewables, frequent change in the weather conditions and the change of load dynamics are the major concerns. MGs, in these situations, are prone to various potential technical challenges like voltage and frequency regulations under various operating conditions. In addition, accurate active and reactive power sharing during parallel operation in both islanded and grid-connected operation might be a challenge. Apart from these, other issues those cannot be ignored and thus taken into account are controlling the high current overshoot during the operation mode transition from islanded to grid-connected and vice versa, restarting the MG systems during grid failure, maintaining minimum operating costs during power exchanges with utility grid etc.

To mitigate these challenges by retaining the controllability, flexibility and security of the power distribution system, robust control techniques should be designed [10-13]. The control methodology could be hierarchical considering all the control layers [12]. The hierarchical control includes three layers of control, i.e. primary (first level), secondary (second level) and tertiary control (third level) layer. These three levels of control techniques are formed based on time response and communication requirements [14]. The control approach that includes communication is categorized as ‘centralized control’ or ‘distributed control’ and the communication-less approach is known as ‘decentralized control’.

Out of these three-hierarchical levels of controls, primary control is mostly decentralized. However, secondary and tertiary controls include some sort of communication. Thus, they can be implemented either in a centralized or distributed manner. The issues in using the communication links at the secondary control layer are reported as communication latency, data drop up, etc. The most important issue is that it is not cost effective if the MG is implemented in the rural areas. However, with the development of robust control systems, the frequency and voltage restoration could be achieved provided the deviations are bounded as per the grid code of a country. Such techniques are called decentralized control for restoration, which avoids an extra dedicated layer in the hierarchical control for MG system.

The review on the combined implementation of decentralized (communication-less) control techniques at both the primary and secondary layers in the hierarchical control structure of AC MG have attracted little attentions in the past. However, with the growing interest and implementation of advanced control techniques in the interfacing of power electronic inverters in case of MGs around the world, a systematic overview of the existing methods combined with decentralized techniques is required.

This paper addresses the droop-based power sharing at the primary control layer and the modified droop for the restoration of the frequency and voltage magnitude deviations those occur because of droop-based proportional power sharing. The control techniques at both the primary and secondary layers are compared individually in the scope of the paper, and summarized shown in the TABLES comprehensibly. In addition to that, simulation comparisons are performed to address selective droop based techniques. Finally, the future research scopes are discussed aiming to improve the reviewed techniques.

The rest of the paper is organized as: section II provides a picture showing various layers of hierarchical control structure of AC MG, and describes overall control functionalities of primary and secondary control layers. Section III describes the issues with the use of communication links at primary and secondary control layers. Section IV reviews the existing droop-based power-sharing techniques to achieve active and reactive power demand, their merits and demerits. Section V describes the communication-less voltage magnitude and frequency restoration techniques in detail, Section VI provides selective simulation comparisons and discusses the future research directions, followed by the conclusion of the reviews in Section VII.

II. Multilayer Control of AC Microgrid

In this Section, the multilayer control of AC MGs is discussed and Fig. 2 shows an overview of its control layers, functionalities and mode of operations.

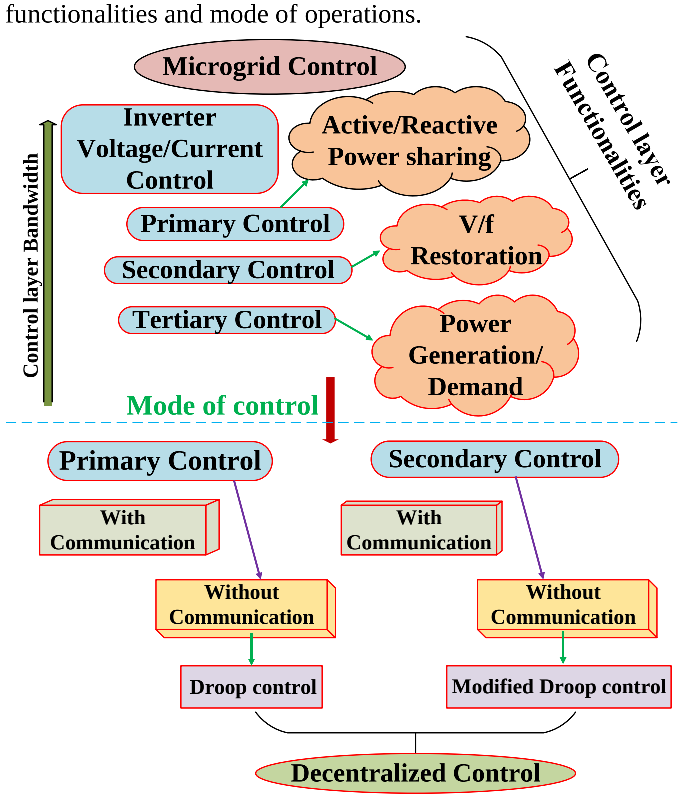

Fig. 2. AC Microgrid control layers, their functionalities and mode of operations.

A. Primary Control

This type of control is implemented in each local controller of the inverter-based DG units. It includes internal voltage and current control along with power control. Inner voltage and current control are meant for regulating the inverter voltage and current output by synchronizing with the grid with the help of proper synchronizing unit. Power controller helps in

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sharing power among DG units in an islanded AC MG. Power sharing can be managed with/without the use of communication links. As this control layer's bandwidth is higher, communication-less power-sharing methods are adopted in an islanded MG to avoid high costs and the impacts of unreliable communication channels. Droop-based techniques are used as communication less power-sharing strategies. A detailed description of droop control can be found in Section IV (B).

B. Secondary control

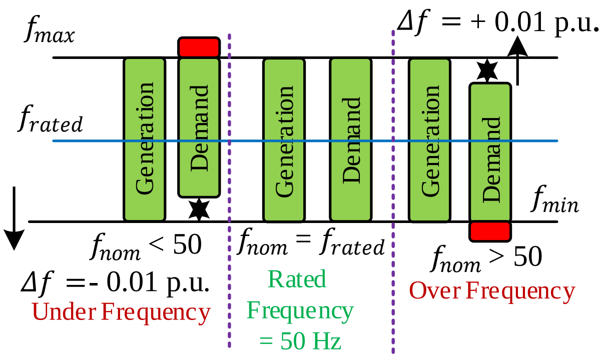

Fig. 3. Operating frequency, under frequency and over frequency conditions of microgrids.

During the power sharing among DG units using the primary droop control, frequency, and voltage are deviated from the set-point values, as shown in Fig. 3. A secondary control level is therefore needed to implement over the primary control level. This level takes care of power quality, voltage and frequency regulation for the islanded MG. Based on the use of communication links it can classified as centralized and distributed control, and as discussed below.

(1). Centralized Control

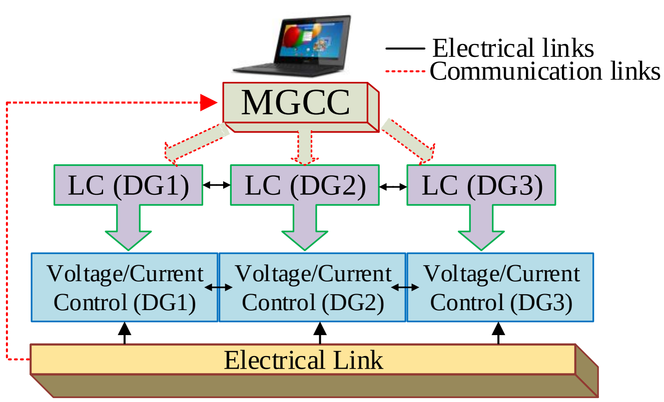

Fig. 4. Centralized control process and its functionalities. MGCC: Microgrid Central Controller, LC: Local Controller, DG: Distributed Generation units.

The central management unit such as MG Central Controller (MGCC) helps MG to operate autonomously during island mode of operation, as shown in Fig. 4. MGCC decides whether the MG will be connected or disconnected from the utility grid based on the comparison between the amount of power generation and load demand [16-20]. In grid-connected mode, it always keeps track of PCC voltage and frequency, sets active and reactive power set points for local controllers [15].

The Distributed Network Operator/Market Operator (DNO/MO) pair takes information from the MGCC. The MGCC communicates with the LLC and provides the set points for them which satisfy the DNO/MO pair requirement. These set points are being followed by control loops such as voltage deviation control loop known as MGVC [19]. An example of laboratory-scale implementation of such hierarchical level of control scheme MGCC with inverter-based intelligent MG is implemented at Alborg University, Denmark [21]. For primary control purposes MATLAB/Simulink software is used and then those controls are implemented to the real system through d-SPACE. The authors of [22] have explained the laboratory set-up, which implements the MGCC architecture and control steps.

(2). Distributed Control

In this section, distributed control methods are described. Fig. 5 shows various distributed control approaches and their implementation processes.

- **Model Predictive-based control**: This approach is the industry standard by its ability to manage large plant systems. It can handle the multivariable control problem and easy to tune, and it considers constraints explicitly. It minimizes the cost function, system steps and those reflecting the deviations from the set points.

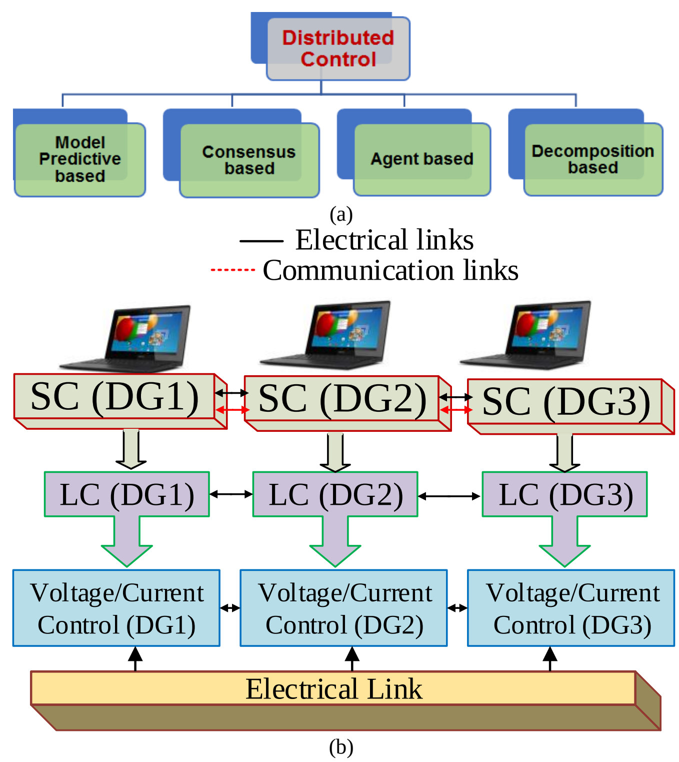

Fig. 5. (a). Distributed control approaches, (b). Distributed Control Process. SC: Secondary Controller, LC: Local Controller, DG: Distributed Generation units.

In order to keep the bus voltages within acceptable limits in a multi-area-based power system, [23]-[24] have used distributed MPC relying on communication between the neighboring control agents. [25] have proposed MPC for voltage and VAR control purpose in an islanded microgrid using mixed logical dynamics technique having efficient and

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fast computing online optimization solver called CPLEX. [26] have decomposed the MPC optimization into transient and steady-state sub-problems and solved it parallel with receding horizon fashion.

- **Consensus-based control**: The "Consensus" word defines an approach, which solves distributed optimization problems. Offers a flexible formulation that ensures extendibility and scalability [27, 28]. Under this technique, each DER unit follows a global objective function for the distributed optimization problem. In order to solve the optimization problem with this technique, use of time-dependent communication architecture is evitable among the neighboring units instead of a dedicated unit. The optimization algorithm used in the consensus-based technique can be without [27] or with constraint [29, 30].
- **Agent-based control**: An agent is an entity, which can act on the environment having the communication ability. It could function as an autonomous body pending on the local goals. The essential characteristics of an agent to become intelligent include pro-activeness, being reactive and being social. Agents can be categorized as centralized, decentralized and hierarchical. A comprehensive review on multi-agent systems (MAS) including its features, challenges and associated technologies is presented in [31, 32]. Java agent development framework (JADE) is primarily used for MAS programming purpose in power systems [33].
- **Decomposition-based control**: Under this control technique, the original optimization problem is divided into several sub-problems. Then, solved using iterative techniques until convergence. Various decomposition techniques are available in the literature [34, 35], such as Auxiliary Problem Principle (APP), Predictor-Corrector Proximal Multiplier method (PCPM) and Alternating Direction Method (ADM).

III. Issues with Communication-Based Control

Communication delays are generally induced during the data exchange between sensors, actuators and controllers across the networks. If the control system design does not consider this delay into account, it degrades the control performance and affects its stability [36-39]. This delay may be constant, time-dependent or even random. When two or more nodes try to transmit simultaneously in a network, a collision occurs between them. The avoidance of this collision is network protocol dependent. Messages with the highest priority are transmitted than those with the lowest priority. When the collision occurs, all the affected nodes stop transmitting, wait for the time duration and then retransmit. The waiting time delays are random for different nodes [40]. Most of the network protocols are provided with transmission retry mechanism but after this time is elapsed, the packets are dropped.

Data packet transmission is either single packet-based or multi-packet based. During single packet transmission, all data are lumped into a single network packet and transmitted at the same time. While in the multi packet-based, data are lumped in different packets so that they do not reach the controller and plant at the same time. The problem with single packet data transmission is the area constraint to accommodate large data into a single packet. Moreover, in the case of multiple data packet transmission, due to multiple delays in receiving the data packet, the controller is unable to access all the plant output data simultaneously for control action [41]. In the case of a feedback-controlled system, a certain amount of data loss is acceptable keeping in mind the stability of the system.

The aforementioned issues with the use of communication architectures in a MG can be avoided by the implementation of advanced control techniques for the inverters. Such techniques can fulfil the requirement of an extra secondary control layer over the primary control layer in the hierarchical control structure of a MG. These are called decentralized control techniques, which avoids any sorts of communications. Existing literatures focusing on decentralized primary (droop techniques) and secondary control techniques in an AC MG are extensively discussed in section IV and V respectively.

IV. Decentralized Control

In a three-phase inverter based MG, the active and reactive powers are calculated in either natural reference frame (abc-frame), or stationary reference frame (αβ-frame), or synchronous reference frame (dq-frame). The phase-angle required for $abc - dq$ transformation is extracted using various PLL techniques [42]. Similarly, in case of single-phase system, in order to calculate power, both in αβ and dq frame, the quadrature signal is generated using various orthogonal signal generation techniques [43-46]. The calculated active (P) and reactive power (Q) is fed to the droop equation to obtain the power-sharing as shown in Fig 6. The details of the various decentralized droop-based power sharing techniques are discussed below.

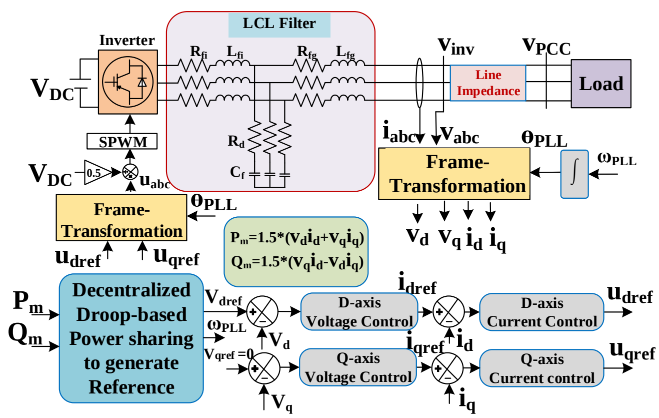

Fig. 6. Outer droop control and inner voltage/current control of a typical grid-forming inverter

A. Droop control

(1). P-ω/V-Q Droop

$$\omega_1 = \omega_0 - m_P(P_1 - P_0) \tag{1}$$

$$V_1 = V_0 - n_Q(Q_1 - Q_0) \tag{2}$$

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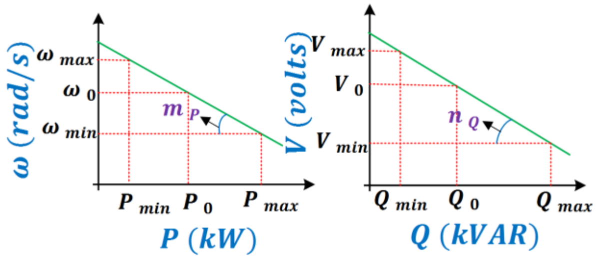

Fig. 7. P-ω / V-Q droop curve.

The conventional droop-based power sharing are shown in Fig. 7 [47-49]. Where, P_0 and Q_0 are the active and reactive power at the nominal operating point (ω_0 and,V_0), m_P and n_Q are the static slopes of the linear conventional droop in (1) and (2).

(2). P-δ/V-Q Droop

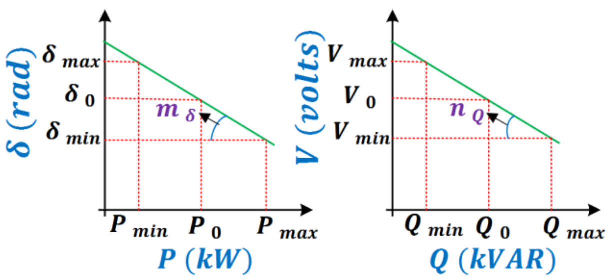

Fig. 8. *P-δ* / *V-Q* droop curve.

$$\delta_1 = \delta_0 - m_\delta(P_1 - P_0) \qquad (3)$$

$$V_1 = V_0 - n_Q(Q_1 - Q_0) \qquad (4)$$

The idea of sharing the active power in proportion to the power angle instead of frequency is proposed in [50]. With this technique, the deviation in frequency can be minimized largely as compared to the frequency droop. The proposed power-sharing technique is described by (3) and (4). In the active power-sharing equation, the frequency (f) is replaced by the power angle (δ) and it is illustrated in Fig. 8.

(3). Adaptive P-δ/V-Q Droop

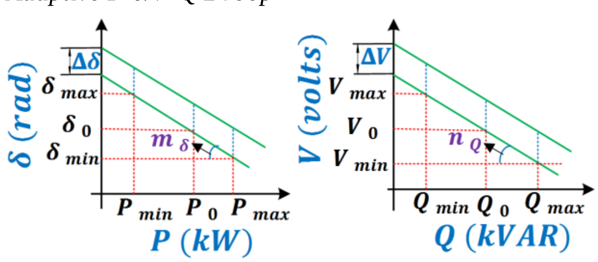

Fig. 9. Adaptive *P-δ* / *V-Q* droop curve.

$$\delta_1 = \delta_0 - m_\delta(P_1 - P_0) + \nabla\delta \qquad (5)$$

$$V_1 = V_0 - n_Q(Q_1 - Q_0) + \nabla V \qquad (6)$$

In order to avoid high droop gain and impact on the overall system stability, supplementary droop is added to the angle droop-based power-sharing technique [51] as shown in (5) and (6). The supplementary terms ($\nabla\delta$ and ∇V) in both active and reactive power sharing are designed based on parameter optimization problem by keeping the closed-loop control of the system stable over a wide range of operating conditions. The droop curves are shown in Fig. 9.

(4). P-ω/Q-adaptive V droop

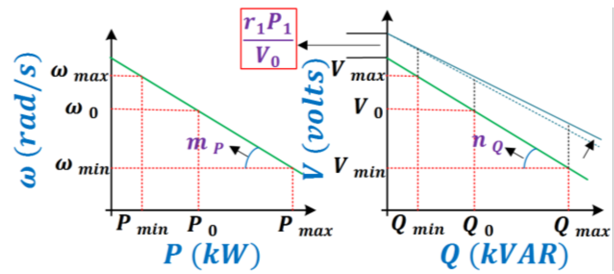

Fig. 10. *P-δ* / Adaptive *V-Q* droop curve.

$$\omega_1 = \omega_0 - m_P(P_1 - P_0) \qquad (7)$$

$$V_1 = V_0 - n_Q(Q_1 - Q_0) + \frac{r_1 P_1}{V_0} \qquad (8)$$

To improve the voltage regulation because of reactive power sharing, an adaptive voltage droop control is proposed in [52]. This technique compensates the feeder impedance drop by adding the terms in the voltage droop control. The power-sharing equations following the proposed idea are shown in (7) and (8). The droop curves satisfying the technique are shown in Fig. 10.

(5). (P-Q)-ω/ (P+Q)-V droop

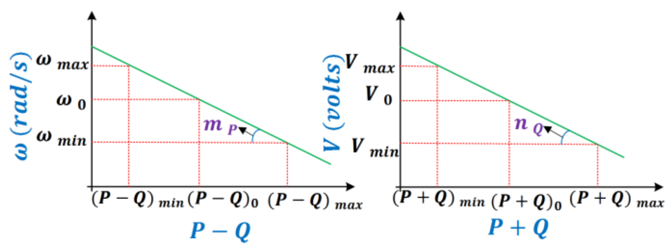

Fig. 11. $(P-Q)-\omega$ / $(P+Q)-V$ droop curve.

$$\omega_1 = \omega_0 - m_P\{(P_1 - Q_1) - (P_0 - Q_0)\} \qquad (9)$$

$$V_1 = V_0 - n_Q\{(P_1 + Q_1) - (P_0 + Q_0)\} \qquad (10)$$

To avoid the line impedance dependency on active and mostly on reactive power sharing, an improved droop control is proposed in [53] and it is shown in Fig. 11. From the droop equation shown in (9) and (10), it is observed that this technique couples the active and reactive power terms. In this way, the proposed technique can be helpful in proving the transient response during the power sharing.

(6). P-ω'/Q-V' Droop

$$\omega_1{}' = \omega_0{}' - m_P(P_1 - P_0) \qquad (11)$$

$$V_1{}' = V_0{}' - n_Q(Q_1 - Q_0) \qquad (12)$$

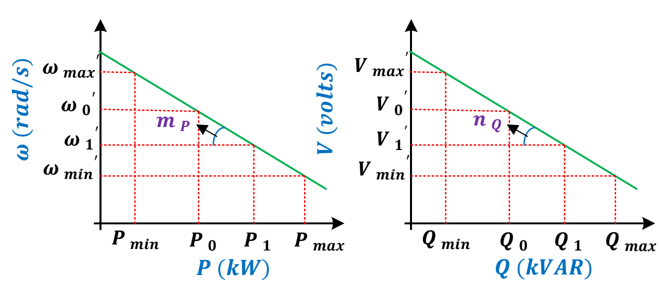

Fig. 12. *P-ω'* / *V'-Q* droop curve.

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The feeder impedances in an MG having comparable resistive and inductive part, always suffer from power coupling term. Thus, using the conventional droop control it is not possible to share the active and reactive power accurately. To avoid such issues, the concept of frame transformation of either power (P, Q) or (ω, V) is proposed in [54]-[56] and the new droop curves are shown in Fig. 12. In this technique, the actual active and reactive power can be frame transformed to achieve virtual power, and they can be replaced in droop control equations. Similarly, the frequency and voltage also can be frame transformed keeping the power terms as it is. The technique of frame transformation is shown in Fig. 13. The droop equations with the virtual terms are shown in (11) and (12).

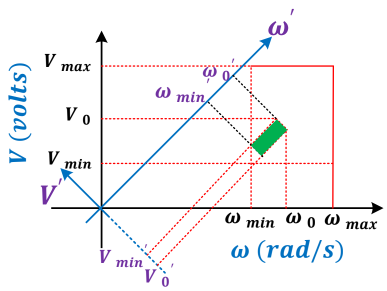

Fig. 13. Frame transformation from actual ω to virtual ω'.

(7). VI droop

To avoid inherent slow dynamics with decentralized droop based power sharing those include P and Q droop characteristics a new VI droop technique is proposed in [57]. The droop curves are shown in Fig. 14. In this droop technique, the dq-axis voltage components (V_{dq}) are allowed to droop following a piecewise linear droop function with respect to dq-components of current (i_{dq}).

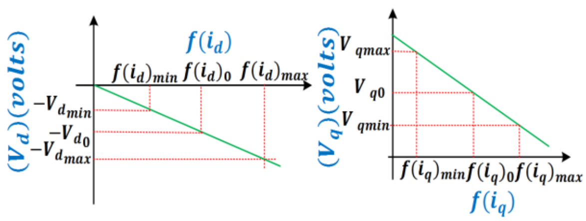

Fig. 14. VI-droop curve.

The droop relations are shown in (13) and (14). The piecewise linear function $f\ (i_d, i_q)$ and $g\ (i_d, i_q)$ follow the relation (15) and (16).

$$V_q = V_0 + (R_T i_q + X_T i_d) - f(i_d, i_q) \tag{13}$$

$$V_d = (R_T i_d - X_T i_q) - g(i_d, i_q) \tag{14}$$

where,

$$f(i_d, i_q) = m_x i_q + l_x i_d \tag{15}$$

$$g(i_d, i_q) = -k_x i_q + n_x i_d \tag{16}$$

(8). Arctan P-ω/Q-V droops

The constant power-frequency droop is replaced with arctangent based active power droop control in [58]. In this way, unlike the fixed gradient-based droop which is always a straight line, this method provides a variation in gradient to active power. Thus, a wide range of frequency bounding can be achieved with this technique. The droop equations are provided in (17) and (18). The proposed droop curve is shown in Fig. 15.

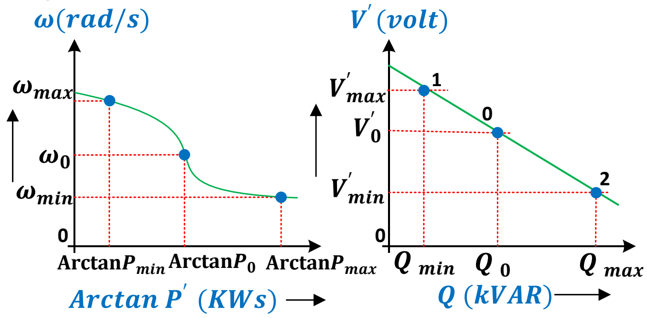

Fig. 15. Arctan P-ω / Q-V droop curve.

$$\omega_1 = \omega_0 - \frac{a_P}{\Pi}\left(\arctan\left(\rho({P_1}' - {P_0}')\right)\right) \tag{17}$$

$$V_1 = V_0 - n_Q(Q_1 - Q_0) \tag{18}$$

(9). Ia-ω/I$_r$-V droop

Instead of sharing the active power and reactive power, the derived active and reactive current components can be shared in proportion to frequency and voltage proposed in [59], and the corresponding droop curves are shown in Fig. 16. The issue of high amount of current flowing during any fault inception can be avoided using the proposed technique.

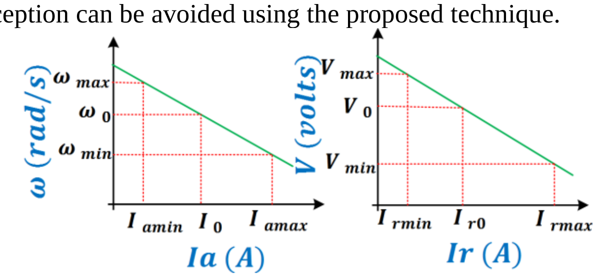

Fig. 16. Ia-ω/Ir-V droop curve.

(10). Signal injection method

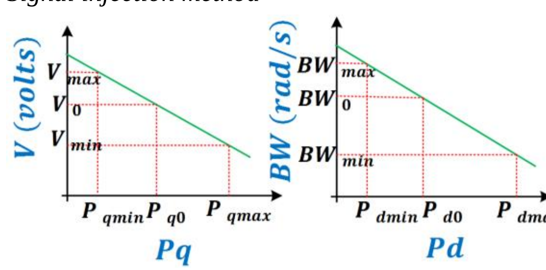

Fig. 17. Droop curve with signal injection.

$$V_1 = V_0 - D_v p_q \tag{19}$$

$$BW_1 = BW_0 - D_{bw} p_d \tag{20}$$

To avoid the unbalance power flow through the feeders connecting the inverters and loads, high-frequency signal injection method is proposed in [60]. The frequency of the signal is a function of active, reactive, and distortion power. The droop for the proposed technique are given in (19) and (20). D_{bw}, and D_v are the boost and droop coefficients. Signal injection based droop curves are shown in Fig. 17.

(11). P-δ/Q-virtual ϕ$_v$ Droop

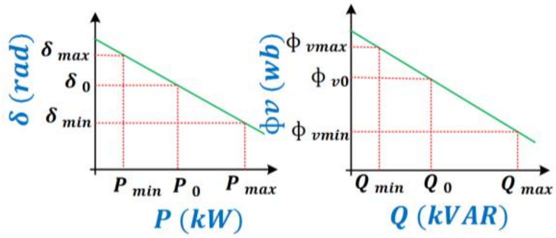

Fig. 18. P-δ / Q-virtual ϕ_v droop curve.

$$\delta_1 = \delta_0 - m_P(P_1 - P_0) \quad (21)$$

$$\phi_{v1} = \phi_{v0} - n_q(Q_1 - Q_0) \quad (22)$$

To enhance voltage regulation during transients and to have minimal frequency deviations, a virtual flux-based droop control technique is proposed [61] as shown in (21) and (22). The new droop curves are shown in Fig. 18. The reactive power is shared in proportional to the estimated flux instead of voltage. It can avoid the use multi P+I controller and PWM modulators generally used for inverter control in AC MG.

(12). P-ω/Q- V dot droop

To make the reactive power-sharing independent of line impedance, a novel droop control employing the derivative of the voltage term in the droop control is provided in [62].

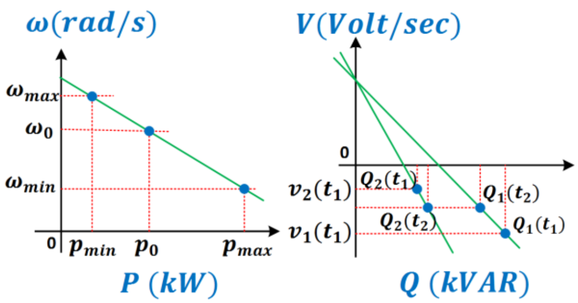

Fig. 19. P-ω / Q- V droop curve.

$$\omega_1 = \omega_0 - m_P(P_1 - P_0) \quad (23)$$

$$\dot{V}_1 = \dot{V}_0 - n_Q(Q_1 - Q_0) \quad (24)$$

The droop equations are shown in (23) and (24). They contain one voltage restoration loop which continuously makes the rate of change of voltage drop zero. This method is dependent on the initial conditions. The droop dynamics are shown in Fig. 19.

(13). P-ω/V-Q Droop with derivative (d (.)/dt) term

$$\omega_1 = \omega_0 - m_P(P_1 - P_0) - m_d\frac{dP_1}{dt} \quad (25)$$

$$V_1 = V_0 - n_Q(Q_1 - Q_0) - n_d\frac{dQ_1}{dt} \quad (26)$$

The idea of combining the static droop gains with the transient droop gains is proposed in [63]. The adaptive droop equations are shown in (25) and (26). They contain a 2-DOF tunable controller. The main objective of the transient droop gains (m_d, n_d) is to damp the low-frequency power-sharing modes. The compensating terms are highlighted in the droop equations.

(14). P-ω/V-Q Droop with combining derivative (d (.)/dt) and integral ($\int(.)dt$) compensation

$$\omega_1 = m_P(P_1 - P_0) + m_d\frac{d(P_1 - P_0)}{dt} \quad (27)$$

$$V_1 = n_Q(Q_1 - Q_0) + n_i\int(Q_1 - Q_0)\,dt \quad (28)$$

A mode-adaptive droop control technique is proposed in [64], which can be implemented both in islanded as well as in grid-connected mode of operation. It includes a derivative term in active power droop to enhance the power loop dynamics during islanding operation. On the other hand, it employs integral control in the reactive power droop to improve the power factor during grid connection. The derivative and integral terms are highlighted in the respective droop equation as shown in (27) and (28).

(15). Frame transformation + Adaptive droop coefficient

$$\delta_1 = \delta_0 - G_P(s) \times FT\{(P_1 - P_0)\} \quad (29)$$

$$V_1 = V_0 - G_Q(s) \times FT\{(Q_1 - Q_0)\} \quad (30)$$

Where,

$$FT\{(P_1 - P_0)\} = Z_g\{(P_1 - P_0)\sin\theta_g - (Q_1 - Q_0)\cos\theta_g\} \quad (31)$$

$$FT\{(Q_1 - Q_0)\} = Z_g\{(P_1 - P_0)\cos\theta_g + (Q_1 - Q_0)\sin\theta_g\} \quad (32)$$

and,

$$G_p(s) = \frac{m_i + m_p s + m_d s^2}{s} \quad (33)$$

$$G_q(s) = \frac{n_i + n_p s}{s} \quad (34)$$

A combination of frame transformation technique for power terms along with the adaptive design of droop coefficients is proposed for power sharing in AC Microgrid in [65] and given by (29), (30), (31) and (32). The droop coefficients contain derivative, proportional as well as integral terms like shown in (33) and (34). Following the technique, an accurate active and reactive power-sharing can be achieved. The reactive power-sharing can be made independent of the line impedances. In this way, the overall stability margin can be improved.

(16). P-V/Q-ω droop

For low voltage AC MG, the line impedances are mainly resistive. So, the dependency of active power changes is more on voltage than frequency. Similarly, the reactive power is shared in proportion with the frequency as shown in Fig 20. So, the new relation for power sharing in LV MG can be provided as (35) and (36) [66].

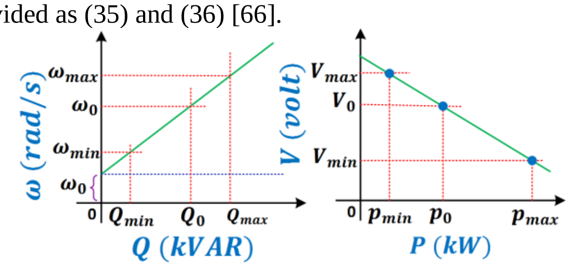

Fig. 20. P-V / Q-ω droop curve.

$$\omega_1 = \omega_0 + m_Q(Q_1 - Q_0) \quad (35)$$

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$$V_1 = V_0 - n_P(P_1 - P_0) \quad (36)$$

(17). Droop in association with virtual impedance concept

Accurate reactive power sharing among the parallel-connected inverters under mismatch of the line impedances through which they connect to the PCC is an issue to be looked upon. One solution to mitigate this problem is the design of virtual impedance. Several studies have been done considering the virtual impedance to achieve accurate reactive power sharing [67]-[70]. Based on this concept, the reference voltage for inner voltage control of inverter can be designed as (37).

$$v_{ref} = {v_0}^* - z_v i_0 \quad (37)$$

Where, z_v is the designed virtual output impedance. The electrical circuit interpretation and phasor representation of the virtual impedance is shown in Fig. 21.

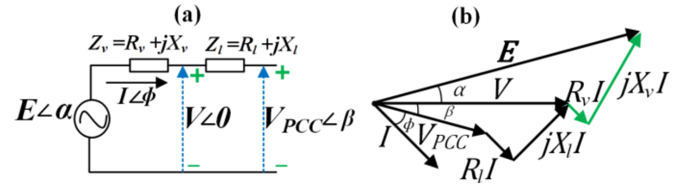

Fig. 21. Virtual impedance concept (a) electrical equivalent, (b) phasor representation.

All the droop-based power-sharing techniques discussed above are summarized in TABLE I. It includes their implementation dependency on system parameters, reactive power-sharing accuracy, transient response, feeder impedance consideration (either resistive or inductive or combination of both), types of load analyzed and consideration of harmonic power sharing.

TABLE I. SYNOPSIS AND COMPARISON OF DIFFERENT DROOP-BASED POWER-SHARING TECHNIQUES

Droop Tech.	Dependency on system parameters	Implementation	Reactive power sharing accuracy	Transient Response	Types of line	Types of load	Harmonic power sharing
P-ω/Q-V [47], [48], [49]	Yes	Easy	Inaccurate	Sluggish	MV	Linear	No
P-δ/Q-V [50], [51]	Yes	Complex	Inaccurate	Sluggish	MV, LV	Linear, nonlinear	No
P-ω/Q-$\dot{V}$ [62]	No	Easy	Accurate	Sluggish	MV	Linear	No
I_a-ω/I_r-V [59]	Yes	Easy	Accurate	Improved	MV, LV	Linear, nonlinear	Yes
Adaptive voltage [52]	Yes	Complex	Accurate	Improved	MV	Linear, nonlinear	No
P-ω'/Q-V' [54], [55],[56]	Yes	Easy	Inaccurate	Improved	LV	Linear	No
P-V/Q-ω [66]	Yes	Easy	Inaccurate	Sluggish	LV	Linear	No
Virtual Flux (ψ) droop [61]	Yes	Easy	Inaccurate	Improved	MV	Linear	No
VI-droop [57]	Yes	Easy	Accurate	Improved	MV, LV	Linear	No
Arctan P'-ω/Q'-V [58]	Yes	Easy	Inaccurate	Sluggish	MV	Linear	No
Signal injection [60]	No	Complex	Inaccurate	Sluggish	MV, LV	Linear, nonlinear	No
Virtual impedance droop [67], [68], [69], [70]	No	Easy	Accurate	Sluggish	MV, LV	Linear, nonlinear	Yes

Note: MV: Medium Voltage and LV: Low Voltage

V. CONTROL TECHNIQUES FOR VOLTAGE AND FREQUENCY RESTORATION: MODIFIED DROOP AND DECENTRALIZED APPROACH

Because of droop-based active and reactive power sharing in inverter-based AC MG, the frequency and voltage magnitude deviate from their nominal value. In order to maintain the grid-code of a country to meet the power quality standards, these parameters (magnitude and frequency) should be restored to their nominal values as shown in Fig 22. The restoration can be done by avoiding communication links at the primary and secondary layer which is called as decentralized secondary control.

Various existing decentralized restoration techniques are used as secondary control to restore voltage magnitude and frequency. In this paper, they are categorized based on the their implementation strategies; such as (a) Classical Proportional/Integral/Derivative (PID) controller based, (b) Digital filter based, (c) Advanced control theory based and (d) others as circuitry philosophy based restoration techniques. Under each category, the individual techniques are further classified depending upon their utilization scope in a MG; which in real time contains source intermittency (such as combination of various sources such as solar PV, wind, battery storage), inclusion of source and load side dynamics, and consideration of line impedance (X/R ratios). Details of these techniques are provided in the following sections.

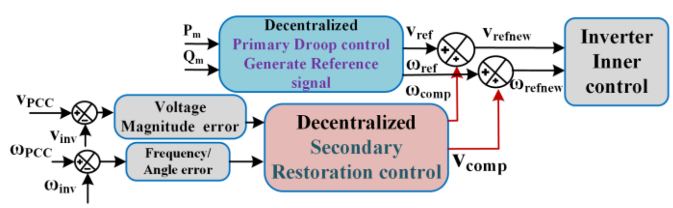

Fig. 22. General framework for Decentralized Secondary Restoration control for droop-controlled inverter.

A. *Classical Proportional/Integral/Derivative (PID) Controller based Restoration*

An adaptive multi-objective fractional order fuzzy PID controller is proposed to mitigate the high cost and degradation factor associated with energy storage units in an

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islanded AC MG [71] while frequency restoration. A modified black hole optimization algorithm is utilized for the adaptive tuning of the non-integer fuzzy PID controller coefficients. The proposed control technique guarantees for frequency stability along with a high efficiency.

Authors have proposed a flexible and scalable master DG inverter concept with no communication which ensures the tracking of nominal values of voltage and frequency without steady-state error [72]. It is a combination of the master-slave concept and droop control. It is assumed in the paper that all the DG units in the MG are either grid-forming or grid-feeding. It uses the potential of every single inverter start-up process from zero voltage. Voltage collapse is used as the initial synchronization of all inverters.

$$t_{rec} = \frac{c}{P_n} + t_{rand} \tag{38}$$

In (38), c is constant which defines how large is the t_{rec}.

During 't_{rec}', the inverter monitors the grid voltage. If it remains close to zero, the inverter can set itself as master. In contrast to the master-slave concept, the active power reserves of all inverters can be used. No additional communication infrastructure is needed as they indirectly communicate via the grid voltage level to determine their role in the islanded grid. When there is an excess of active power, the voltage will increase, and it goes beyond the voltage limit. Then the master unit changes the grid frequency to stop the active power flow and the voltage increment. The difference between the master and follower control is that, in followers the integral part is active under certain conditions.

Frequency regulation of an isolated inverter-based MG through voltage regulation process is proposed in [73]. It does not require any communication as it will use the voltage and frequency of the DG unit as feedback signal in its local controller. This control technique uses the load power sensitivity on the operating voltage to maintain the system active power balance. In that way it controls the frequency. The input to the controller is the system frequency deviation which passes through a conventional PI controller to avoid steady state error. Another gain factor k_{vfc} provides the damping to the output signal of the PI ensuring that no overshoot appears in controlling the frequency. To maintain the phase between input and output of the voltage regulator, authors in [73] have used a first order lead-lag compensator. The voltage is kept within the desired range to fix VFC_{min} and VFC_{max}. The output of the controller is added to the voltage reference as shown in Fig. 23.

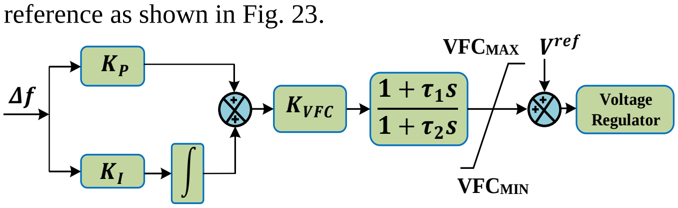

Fig. 23. Frequency restoration control through voltage regulation [73].

Based on a time domain technique frequency and voltage balance have been performed in [74]. Positive and negative sequence components of a three-phase signal are extracted using this technique without the use of any transformation matrix. The extraction of three phase signals is done using symmetrical component theory.

A quasi-hierarchical decentralized control method proposed in [75] to restore frequency and maintain economic dispatch. The proposed control is a three-level based control and all these levels are implemented locally to a DG unit which avoid the use any communication link. The deviations in the frequency and power after the implementation of the primary control level are mitigated using low pass filter (LPF). Decentralized secondary control is implemented in each DG unit to restore the frequency by implementing an LPF with a high gain in the secondary level.

Authors in [76] have proposed a technique that implements both frequency recovery and accurate active power sharing simultaneously. They mentioned that upon a load change, the frequency restoration process will take place using PI controller. The amount of extra active power needed will be distributed among all the DG units depending upon a predetermined ratio using a compensation control scheme.

In order to avoid difficulty and extra time taking in tuning the PI controller gain parameters, PSO based algorithm is adopted in [77] for a hybrid generator system. In this paper, each generator is governed with one PI controller to mitigate the frequency mismatch. By this technique, authors have claimed to achieve less overshoot, less settling time as well as reduced oscillations while restoring the frequency.

A wireless and multifunctional droop control is proposed for distributed storage units in order to restore voltage and frequency in an islanded AC MG [78]. The proposed droop control implements the state of charge-based *P-f* droop. For reactive power sharing and voltage restoration integral of reactive power with voltage droop is used. Compensation term is considered as proportional to the active power sharing error at steady state, which is almost zero.

The improved droops are shown in (39) and (40):

$$\omega = \omega_0(1 - K_P P - K_{SoC} SoC) \tag{39}$$

$$E_{t+} = E_0 - K_Q \int_0^{t-} Q\,dt + \int_0^{t-} P dt \tag{40}$$

According to the above equations, the energy sources with higher SoCs will provide higher frequency and deliver more active power. Voltage-reactive power droop is strongly influenced by the historical information of reactive power.

A multi-input multi-output control strategy is proposed for inverter-based MG implementing *dq*-based control. Integral and repetitive control theory has been proposed to regulate the voltage under both balanced and unbalanced grid condition [79]. Enhanced PLL technique is proposed to estimate the grid parameters to include in the *dq*-based control. Enhanced PLL is further modified to restore the system frequency. The proposed repetitive controller for voltage regulation under unbalance and harmonically polluted load is shown in Fig 24.

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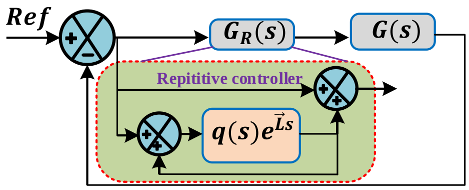

Fig. 24. Implementation of repetitive controller.

B. Digital Filter based Restoration

A switching control in the secondary control level of DG unit is proposed [80], which follows a time-dependent protocol and independent of any communication link. The switch control, which is generated from the secondary level, employs the PI control that follows a signum based function rule as shown in Fig 25. A time-based protocol controls the variable in the signum function. With the proposed signum based switching control signal, hunting problem can be avoided. The time-dependent protocol used in this technique is based on any event detection strategy as shown in Fig 25(b), which considers both percentage change of active power and frequency as a threshold.

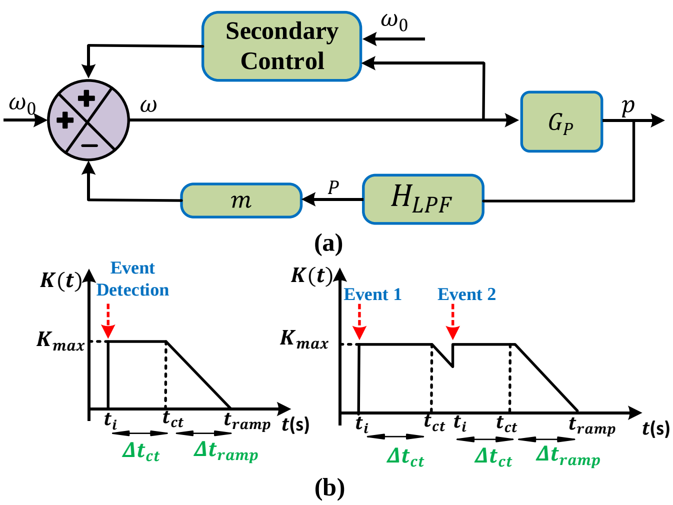

Fig. 25. Combined control of primary and secondary layers [80].

Ref [81] has introduced a multi-layer control for inverter based DERs and claimed to have not used any intercommunication between the control layers. The restoration technique is implemented using a proportional gain and a low pass filter whose cut off frequency is calculated using first order Pade's approximation. The proportional gain is selected using root-locus technique considering the system accuracy and robustness.

The concept of the implementation of a digital Band Pass Filter (BPF) in the primary droop control for frequency restoration in AC Microgrid is proposed in [82]. The BPF is formed by the cascaded connection of a recursive discrete Fourier transform (DFT) and inverse DFT. The authors have shown that the frequency restoration occurs in 20 ms using this technique for various plug and play operations.

Frequency/voltage restoration using wash-out filter has been considered as an equivalent secondary control in [83]. Authors of this paper have compared the performance of the secondary control and washout based control for the restoration process. The parameters used for the secondary control have been used for designing washout filter under some assumptions. In the washout filter based restoration no secondary layer is required. The LPF is cascaded with the washout (HPF) filter to form a BPF, which does not allow the DC content of the signal in its bandwidth range as shown in Fig 26. The cut-off frequency of the HPF has been chosen lesser than that of the LPF to ensure the system dynamic stability is improved. In the conventional droop-based power sharing the rate of change of voltage/frequency and active/reactive power attains zero in the steady state. So, under this condition the amount of frequency/voltage deviations is added to the dynamics of the conventional droop equation. At the steady state the zero value of ROCO frequency/voltage will drive the frequency/voltage deviations value to zero, thus they restore their nominal values. No communication link is required for this kind of control technique, as it is implemented in each DG unit locally [85]. Based on the proposed control technique the improved droop equations are as shown in (41) and (42):

$$\omega^* = \omega - m_P * \frac{S}{S + K_P} * (P - P^*) \tag{41}$$

$$V^* = V - n_Q * \frac{S}{S + K_Q} * (Q - Q^*) \tag{42}$$

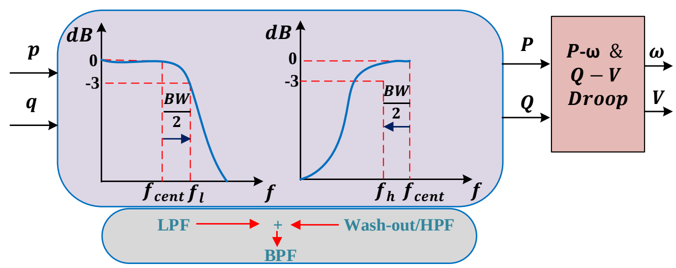

Fig. 26. Concept of wash-out filter.

Where the washout filter (first order HPF) transfer function is given by $\frac{S}{S+K_P}$. From the above equations, it is noted that the droop coefficients and time constant of the HPF should be chosen properly to restore frequency and voltage exactly to the set values.

In order to increase system dynamics in an islanded inverter-based AC MG without the use of communication link, a second order washout filter based technique is proposed instead of first order [84]. In this paper, the delay associated with the LBC lines is considered as shown in Fig 27. In order to mitigate that delay, in the wash-out based restoration process a first order lead compensator has been proposed by the authors. The lead filter is meant for the improvement of the dynamic performance of the system.

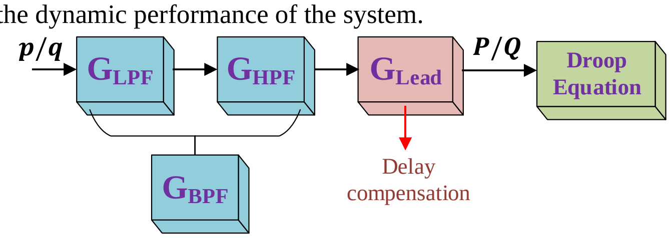

Fig. 27. Washout filter with first order delay.

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A communication-less voltage restoration technique is proposed using Kalman filter-based voltage estimator for estimating the PCC voltage change. In further steps, Model Predictive Control is proposed for controlling the bus voltage optimally [86]. The estimation of voltage can be done dynamically. This control technique can optimally adjust the voltages in a multi bus system unlike the offset control of conventional PI controller. The combination of high-pass filter-based droop and virtual capacitance droop is implemented in a hybrid energy storage system-based MG [87]. Thereby to restore the frequency fluctuations and voltage deviations. The analysis is done for various load dynamics.

C. Advanced Control Theory based Restoration

H_∞ control theory for proper load sharing between multi-operated distributed power generators is proposed in [88] as shown in Fig 28. By this technique the transient response of the system is improved, and robustness of the system will increase again the measurement noise and system parameter variations. The H_∞ based improved droop proposed is based on LMI approach. To maintain load sharing accuracy at such low charging rate, the weighing function at the controller output is increased in the low frequency domain. The weighing functions at the plant output are meant for robustness of the system and takes low gain characteristics for the improvement of the transient response.

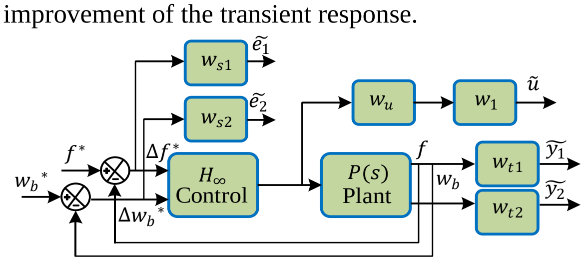

Fig. 28. Time dependent protocol for single and multi-event scenarios [88].

A coordination between DERs in an islanded mixed source based MG is proposed, where the frequency regulation is taken care of by sharing the unequal transient load between gensets and inverter based DERs [89]. Inverter based DERs have low inertia that is why under the circumstances of large load variations their frequency of operation deviate from the MG frequency. At this stage, energy storage systems are helpful in restoring the frequency by supplying extra amount of power. In this paper for supplying the extra amount of energy is being fed by the gensets by the use of their reserved inertia and governor characteristics. Due to lack of inertia, if at any case the inverter based DER is unable to supply their part. Then, the authors have suggested using smart load to shed some of the non-critical load for a certain period until the frequency reaches the calculated frequency nadir value. Once the frequency is recovered, then those shed loads can be brought back to the MG system. The droop control for inverter based DER is modified and a lead-lag compensator is introduced in order to reduce the transient load sharing.

A fuzzy logic-based tuning is proposed in [90-92] for a micro hydro power plant to restore the frequency in rural areas in-stead of load shedding during power imbalance. The proposed fuzzy logic control processes 7 inputs, five membership functions and five outputs. Based on the fuzzy rules the outputs are generated to tune a PI controller gain which will help in restoring the frequency. The fuzzy logic controller is designed for any specific frequency error.

A coordination architecture considering the appropriate charging profile of battery-based energy storage system based on distributed decision-making mechanism is proposed for islanded AC MG [93]. The mechanism uses the local measurements for to determine the operational mode without any communication link. It operates on bus signaling technique, so that all the DG units will have global perception regarding the operation of the MG. Frequency restorations in AC MG using decentralized linear quadratic regulator is proposed in [94]. The authors have claimed not to use any communication links during the restoration process.

D. Others as Circuitry Philosophy based Restoration

The merged frequency unqualified zone that result from the conventional primary control to an acceptable zone by the secondary control with the help of a mathematical based projection function addressed in [95]. A novel frequency restoration technique along with reactive power sharing strategy is proposed in [96] which do not require any kind of communication link in frequency restoration process as shown in Fig 29. First to mitigate reactive power error, reactive power compensation process (RCP) and next frequency restoration process (FRP). The conventional droop control is improved to implement these two processes. A reactive compensation term is added to the (*w/P*) droop equation assuming that the steady state frequency is the same for all DGs and accurate active power sharing. The compensation term uses an increasing/decreasing compensating gain for the entire process.

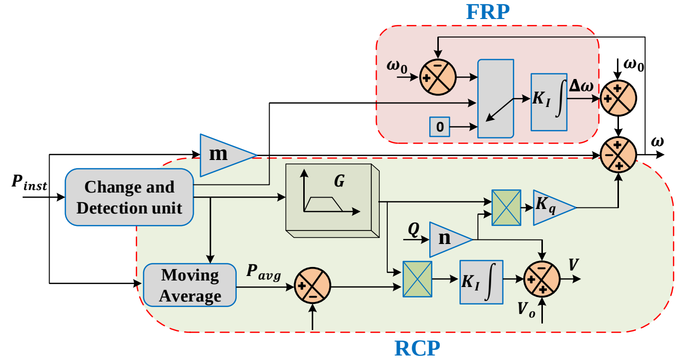

Fig. 29. Coordination control between reactive power compensation (RCP) and frequency restoration process (FRP) [96].

Frequency restoration in case of PV solar connected power system using unscented Kalman filter based dynamic estimation is proposed in [97]. Uncertainties based on solar irradiance variations in case of PV have been considered in the scope of the paper. Voltage and current measurements are done by the use of PMU. The proposed method uses only local variables like voltage and current for state estimation and therefore requires no communication link. The proposed control technique has used PI controller for frequency restoration by estimating the frequency with the help of DSE. The estimated and actual frequencies are found to be similar.

A secondary droop control is proposed along with primary droop in order to restore the MG system voltage and frequency in an islanded inverter-based AC MG [98]. The

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proposed technique does not require any communication link as it is implemented in each DG unit locally. Frequency restoration is occurring basically by supplying steady state power error. The new droop concept is as follows. While restoring voltage/frequency, the compensation terms follow a ramp function in order to ensure that it should not clash with primary droop-based power sharing. Accordingly ramp rate and restoration time has been designed in the paper. Authors have assumed the restoration rate is the same for all the connected DGs.

A load shedding based strategy is proposed for frequency restoration for the autonomous operation of an AC MG [99]. Deferral and sensitive loads are two different types that have been taken into account for load shedding based control implementation. This technique does not need any communication link for frequency regulation. A power limiting strategy has been adopted for each DG unit to avoid output power violation. Once the frequency deviation is below that threshold due to any transient disturbances, then corresponding percentage of deferral load is shaded with some delay time which is considered as restoration time.

A voltage compensation technique is adapted for PCC voltage restoration in an islanded AC MG [100]. The droop control for power sharing is improved with compensation algorithm, so that communication links are not required for this kind of restoration process. Insight to voltage restoration under same and different feeder impedance cases have been considered in the scope of the paper. Firstly, the voltage drop in the feeder impedance is calculated as (43) and (44): Under this compensation, the slope of the Q-V droop is not affected as mentioned in (45). For unequal line impedance case, a constant is multiplied to the actual line impedance (R_E, X_E) to calculate the compensation value.

$$\vec{V}_{\mathrm{drop\_E}} = 2*(\frac{P_{DG}*R_E + Q_{DG}*X_E}{V_{rev}} + j\frac{P_{DG}*X_E - Q_{DG}*R_E}{V_{rev}}) \quad (43)$$

$$\vec{V}_{PCC} = \vec{V}_{rev} - \vec{V}_{\mathrm{drop\_E}} \quad (44)$$

Voltage compensation term can be written as:

$$V_{comp} = K_p*(V_0 - V_{PCC}) \quad (45)$$

A load ramp control method is proposed to regulate the frequency in an islanded AC microgrid containing non-linear load like power electronics load [101]. The authors of the paper have claimed that the technique is communication free. The ramp control forces the load to consume more real power in case of frequency increases the nominal value and vice versa. The slope of the ramp calculated based the normal and minimum allowable active power values of power electronics load along with the minimum threshold and minimum allowable frequency limit of the MG. Communication free coordinated frequency control with the help of demand side management capability proposed. Thermostatically controlled load has been used for manipulating the frequency restoration [102]. To model TCL first order differential equation used. Frequency manipulation occurs using three main blocks such as (i) aggregation block which measures the frequency deviation and checks whether it falls in the prescribed range. If it does not fall in the range, the amount of TCLs manipulated follows the following strategy: (ii) The temperature control block, the operating states of TCLs to the TCL control maintain the temperature in the specified range and finally (iii) TCL control block decides the actual amount of TCLs to be manipulated based on the operating state information and TCLs demanded by aggregation block.

The summarization of above discussed various modified droop-based voltage magnitude and frequency restoration techniques are provided in TABLE II.

TABLE II. SUMMARY OF VARIOUS COMMUNICATIONS-LESS SECONDARY CONTROL TECHNIQUES.

Restoration Category	Used Technique	Source Dynamics	Source Intermittency	Load dynamics	Line impedance
Classical Proportional/Integral /Derivative (PID) Controller based	Multi-objective fractional order P+I+D controller [71]	considered	considered	considered	not discussed
	Adaptive P+I controller [72]	not discussed	not discussed	considered	(R/X) >1
	Use of PI + Gain + Lead-lag compensator [73]	Considered (only wind speed)	considered	considered	not discussed
	P controller [74]	considered	not discussed	not discussed	(R/X) < 1
	P controller + LPF [75]	not discussed	not discussed	not discussed	(R/X) < 1
	P+I controller [76]	not discussed	not discussed	not discussed	not discussed
	P+I controller Gain tuning using PSO [77]	considered	considered	considered	not discussed
	Active power compensation using P+I control [78]	not discussed	not discussed	not discussed	(R/X) < 1
	Integral + Repetitive control [79]	not discussed	not discussed	considered	not discussed
	Low pass Filter [80]	not discussed	considered	considered	both (R/X) >1 and <1
Digital Filter based	First order Pad´e approximation with a low-pass filter [81]	not discussed	not discussed	not discussed	(R/X) < 1
	Recursive DFT+IDFT based BPF [82]	not discussed	not discussed	not discussed	(R/X) < 1
	Band Pass Filter [83]	not discussed	considered	considered	(R/X) < 1
	Band Pass Filter + Lead compensator [84]	not discussed	not discussed	considered	(R/X) < 1
	Band Pass Filter [85]	not discussed	considered	considered	(R/X) < 1
	High-pass filter [86]	not discussed	not discussed	considered	discussed
	Kalman Filter-based estimation [87]	not discussed	not discussed	not discussed	not discussed

Advanced control theory based	Using H_∞ control [88]	not discussed	not discussed	not discussed	(R/X) <1
	Lead-lag control [89]	not discussed	not discussed	not discussed	not discussed
	Fuzzy logic control [90], [91], [92]	not discussed	not discussed	not discussed	not discussed
	Voltage and frequency signaling technique [93]	considered	considered	not discussed	not discussed
	Decentralized linear quadratic regulator (LQR) [94]	not discussed	not discussed	not discussed	not discussed
	Using a mapping function [95]	not discussed	not discussed	not discussed	(R/X) <1
Others as Circuitry Philosophy based	Through the compensation of reactive power in the droop [96]	not discussed	considered	not discussed	both (R/X) >1 and < 1
	Unscented Kalman filter based state estimation [97]	considered	not discussed	not discussed	not discussed
	Secondary droop + rate limiter [98]	not discussed	not discussed	not discussed	not discussed
	Under frequency load shedding Tech. [99]	not discussed	not discussed	not discussed	(R/X) < 1
	Line impedance drop based compensation [100]	not discussed	not discussed	not discussed	both (R/X) >1 and <1
	Ramp control of load power [101]	not discussed	not discussed	not discussed	not discussed
	Coordination control between battery, PV and TCL [102]	not discussed	not discussed	not discussed	not discussed

VI. Simulation Comparisons of Selected Droop Techniques

A MG model as shown in Fig 30, was created using MATLAB/SIMULINK to benchmark five different droop controllers. It considers two equal rated voltage source inverters (VSIs) connected in parallel with two constant resistive and inductive loads, lines of high *R/X* ratios and mismatched inverter output impedances. Conventional cascaded inner voltage and current controller were implemented in each inverter in the MG model. The cascaded voltage and current control model in the *dq*-frame for each inverter is shown in Fig 31. The inverter controller along with the system parameters are provided in Table III and Table IV.

The droop controllers considered for simulation are:

Droop 1: Linear active power-frequency droops with linear reactive power-voltage droop [47]
Droop 2: Arctan power-frequency droops with linear reactive power-voltage droop [58]
Droop 3: Linear power-angle droops with linear reactive power-voltage droop [50]
Droop 4: Linear power-frequency droop with virtual impedance compensated linear reactive power-voltage droop [68]
Droop 5: Linear power-frequency droop with linear Q-V dot droop [62]

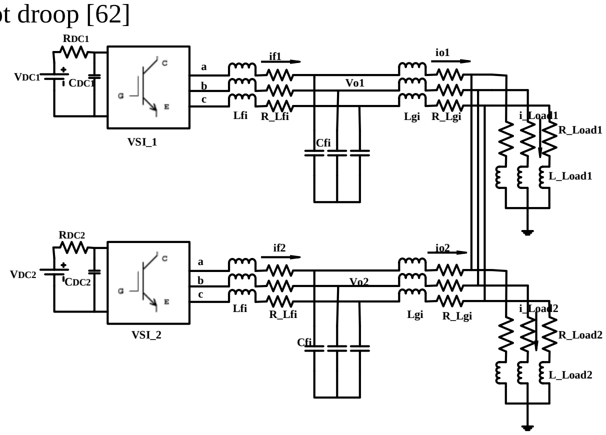

Fig. 30. Inverter-based MG model used for simulation comparison

The droop coefficients were designed to have allowable voltage droop in the system of 5% and an allowable frequency droop as 0.5%. Care was taken to keep these design goals same for all the droop controllers to have a uniform comparison.

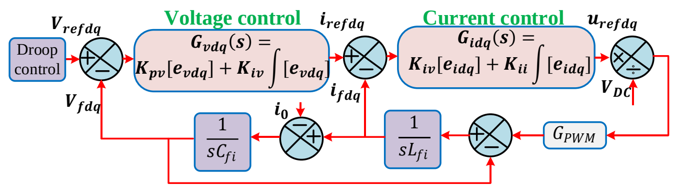

Fig. 31. Inner voltage/current control used for inverter modelling.

Table III: System and controller parameters of MG model

Parameter	Value
R_L_{fi}	40 mΩ
L_{fi}	2.5 mH
R_d	3.3 Ω
C_{fi}	100 µF
L_{g1}	0.75mH
L_{g2}	0.5 mH
$R\_{L_{g1}}$	45 mΩ
$R\_{L_{g2}}$	30 mΩ
K_{pi}	20.5
K_{ii}	40e3
K_{pv}	0.05
K_{iv}	390
Inverter P nominal rating (W)	100e3 W
Inverter Q nominal rating (VAR)	60e3 VAR
System Frequency (Hz)	50 Hz
System Voltage (V)	240 V
Load 1 (KVA @ 240V)	50+30j
Load 2 (KVA @ 240V)	100+60j

Table IV: Droop control parameters for each of the five cases

Parameter	Value
Voltage droop gain n_q	2e-4
Linear Droop gain m_p	1.57e-5
Arctan k	3.14
Arctan r	1e-4
Arctan P_o	50 kW
Angle droop m_φ	1e-6
Virtual R VSI_2	0.015 mΩ
Virtual L VSI_ 2	0.25 mH
QV droop gain	0.2
QV restoration gain	1000

A common test case is simulated for the selected five droop controllers to understand their power-sharing dynamics. The two inverters in the model were assumed to be initially synchronized under no-load conditions. Then Load 1 is connected at time t = 0 sec, followed by connection of load 2

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at t = 1 sec. The simulation time was kept for 2 sec during all the considered droop technique implementation.

Firstly, the impact on the voltage and frequency at the inverter output during power sharing is shown in Fig 32. It is observed that the Q-V droop curve having the same droop coefficient as the Q-V droop yields very similar response; On the other hand, both the arctan and angle droop have increased stability over the V-f droops. Interestingly, the virtual impedance droop has worse voltage regulation at low voltages; however, improves the voltage regulation properties at higher power outputs as seen in TABLE V. The Q-V droop curve offers quick voltage response; however, this comes at the cost of poor voltage regulation. It changes the voltage relentlessly until reactive power is shared properly. This can be seen when load 1 is connected, where the voltage is almost 50% greater than the nominal. Due to this, it does not fit for use in conventional power systems that require strict voltage limits.

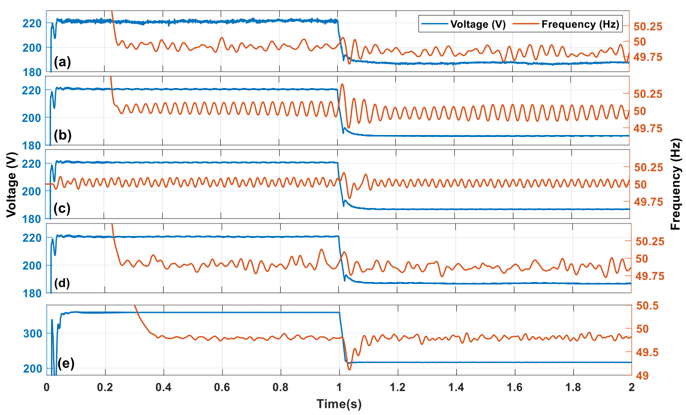

Fig. 32. Voltage and frequency response of (a) Droop1, (b) Droop2, (c) Droop3, (d) Droop4, (e) Droop5

TABLE V: VOLTAGE RESPONSE COMPARISON OF FIVE DROOP TECHNIQUES

Droop	Settling time (s)	Regulation w/ Load 1	Regulation w/ Load 1 & 2
V-f	1.095	-7.6%	-22.00%
Arctan	1.054	-8.12%	-22.23%
Angle	1.057	-8.06%	-22.19%
Virtual Z	1.218	-8.97%	-25.04%
Q-V dot	1.02	+49.5%	-9.79%

Each of the considered droops achieve greater frequency regulation as per Fig 32 and TABLE VI findings. The arctan droop reaches the same frequency at full load however, it maintains 50 Hz at the designed opearting point.

TABLE VI: FREQUENCY RESPONSE COMPARISON OF FIVE DROOP TECHNIQUES

Droop	Frequency load 1	Frequency load 1 & 2
V-f	49.918	49.799
Arctan	50.1674	49.8037
Angle	50.026	50.026
Virt. Z	49.92	49.861
Q-V dot	49.905	49.814

The real power sharing dynamics, as shown in Fig 33, were investigated for the same load-switching scenario, for all the five droop techniques. It is shown that all the frequency coupled droop techniques achieve equal power-sharing. The power-sharing accuracy in all the cases is provided in TABLE VII. The angle droop is the only one that fails to share power accurately. This occurs as the real power-sharing is determined by the ratio of line reactance and a gain term as (46).

$$\frac{P_1}{P_2} = \frac{X_{1out} + X_{1line} + m_1}{X_{2out} + X_{2line} + m_2} \tag{46}$$

If the line inductance is considerably low as is possible in low voltage microgrids, the power sharing will be more accurate. An increase in gain will also serve to increase the power sharing accuracy, but will lead to reduced stability margins.

TABLE VII: REAL POWER SHARING COMPARISON

Droop	Load 1 inverter 1 / 2 mismatch (%)	Settling Time (ms)	Load 1 & 2 inverter 1/2 mismatch (%)	Settling time (ms)
V-f	49.99/50.01	378.5	0.4997/0.5003	495.5
Arctan	50/50	259.6	49.99/50.01	332.2
Angle	40.83/59.17	120.9	41.08/58.92	115.9
Virt. Z	49.09/50.91	433.8	47.85/52.15	449
Q-V dot	50.05/49.95	unsettled	49.95/50.05	unsettled

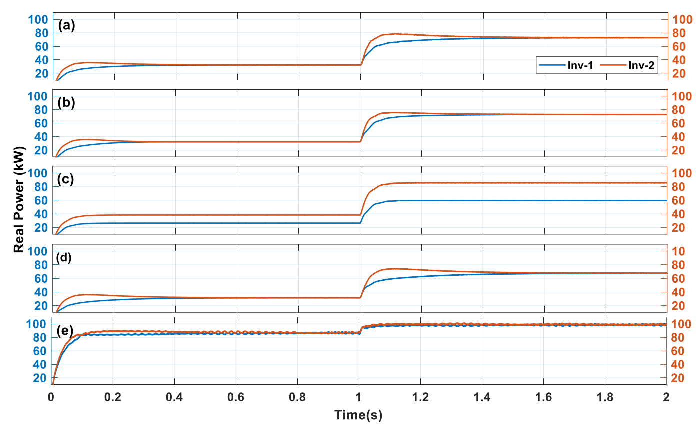

Fig. 33. Real power response of (a) Droop1, (b) Droop2, (c) Droop3, (d) Droop4, (e) Droop5

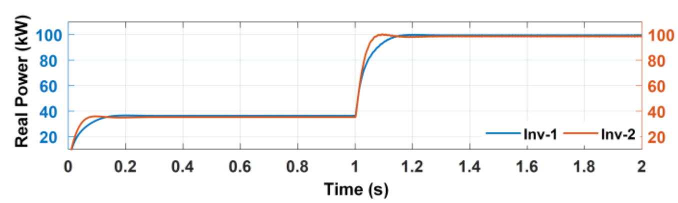

Fig. 34. Angle droop power sharing for resistive line.

With the inductance dropped to a hundredth the original, real power is shared very accurately 49.95%/50.05% between Inverter 1 and Inverter 2, respectively as shown in Fig 34. Hence it would be a useful choice for very high R/X ratio lines. The angle droop and arctan have a quicker settling time than the V-f droop whereas, the Virtual impedance and Q-V droop curve reduce the settling time to try and to improve the reactive power sharing.

TABLE VIII: REACTIVE POWER SHARING COMPARISON

Droop	Load 1 inverter 1 / 2	Settling time	Load 1 & 2 inverter 1/2	Settling time

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	mismatch (%)	(ms)	mismatch (%)	(ms)
V-f	42/58	122.1	43/57	165
Arctan	41.51/58.49	135.2	42.8/57.2	133.6
Angle	42.63/57.37	127.1	42.8/57.2	123.6
Virt. Z	49.09/50.91	220.3	47.85/52.15	149.3
Q-V dot	48.38/51.62	unsettled	49.93/50.07	unsettled

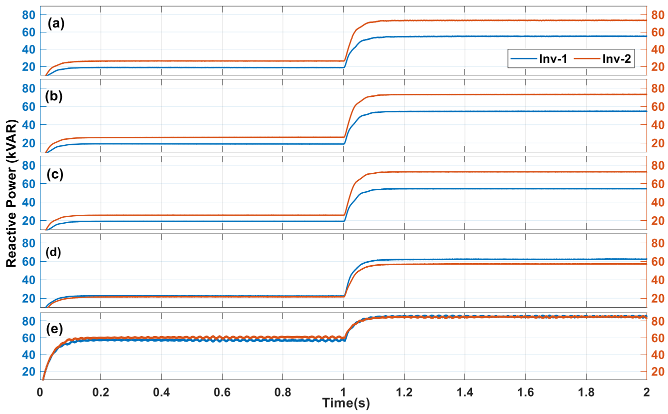

Fig. 35. Reactive power response of (a) Droop- 1, (b) Droop- 2, (c) Droop- 3, (d) Droop- 4, (e) Droop- 5.

Fig 35 and TABLE VIII, that there seen very little difference between the V-f, arctan and angle droops in terms of reactive power-sharing accuracy and settling time due to common implementation of the Q-V droop. The virtual impedance and Q-V droop curve can achieve much more accurate reactive power sharing, but it comes at the cost lower settling times. These low settling times could make them undesirable for use as renewable sources can have high variability and may require faster response times for system stability.

In a nutshell, the simulation study and dynamics comparison of the selected five droop-based power-sharing techniques illustrate that the angle droop is very powerful given the right circumstances. Its response times are the fastest when compared with other droops and maintains the frequency at the nominal value. It is not fit for use in all situations due to low real power-sharing accuracy when large mismatched output reactance is present. However, it fits perfectly into low voltage microgrids that have equal output impedance or negligible line reactance. Even with large mismatched line impedances it could be paired with a virtual impedance to correct its real power-sharing. This will trade-off some of its quick response time. The arctan droop technique proves to be superior to the linear function in achieving faster response times and stability. The Q-V droop curve does achieve accurate power sharing; however, it has very long settling times. Also, only allows very little voltage control making it largely impractical for use. A much more flexible method to improve the power sharing of a system is to use virtual impedance. By which to alter the characteristics of the system by being able to alter the effective output impedance to desired values. It provides accurate power-sharing with improved stability at the cost of slightly increased settling times.

VII. FUTURE RESEARCH DIRECTIONS

Though communication-less primary and secondary control techniques can achieve power-sharing and voltage/frequency restoration in a MG, there are many aspects for in-depth research. The techniques discussed in section IV (for power-sharing) and sections V (voltage/frequency restoration) have not considered all the potential issues while proposition of the techniques in the AC MG. There are many aspects where further research can be carried out aiming to improve the existing techniques. Most of them are listed and discussed as given below:

- *Trade-off between active power sharing and frequency deviation:* The future research could focus on the trade-off between this power sharing and frequency regulations. By designing a robust and the hybrid, droop control method [103].
- *Power sharing dependency on line impedance:* The reactive power droop is mainly dependent on voltage magnitude for MV MG and on frequency in LV MG. They are highly influenced by the electrical distance i.e. line impedance (either resistive or inductive or combination of both) between the inverter output terminal and the PCC [104]. Various newly proposed droop techniques can include the line impedance while sharing active/reactive power demand.
- *Stability analysis during power sharing:* The stability of MG is a trending topic to be studied [105]. The frequency fluctuations in a MG depends on its type of operation e.g. islanded or grid connected. During the islanding process, large oscillations in the frequency characteristics are observed. In such scenario, the proposed droop control should undergo stability check to decide the operating conditions for safe operation [113].
- *Harmonic load sharing:* Most of the domestic loads connected to inverters draws harmonic current [106]. Newly proposed droop technique assumes the load as linear type for which the proposed droop becomes helpful in power-sharing. However, in case of non-linear load, the operation of droop equation should be researched and propose necessary modifications [114].
- *Fault-ride through operation:* Inverters connected to the point of common coupling (PCC) should be able to ride through the voltage sag issues caused by various symmetrical and unsymmetrical faults [107], [108]. So, the future research should focus on the reliability studies of the proposed power-sharing or voltage restoration control during such fault scenarios.
- *Source intermittency and load dynamics:* As the renewables are intermittent and the customer's power demand is non-linear [109]. The control algorithms should consider the real variable power generations instead of a constant power source. Moreover, the MG is prone to power quality degradation, so the impact of weather to the weather-dependent sources and their abrupt power output variation should consider during load-support controller design [110]. Likewise, customers' varying power

demand, load dynamics, and load characteristics should also be considered.

- *Bidirectional peer-to-peer (P-P) energy transactions:* The increasing use of P-P energy transactions will add complexity to the power flow directions [111]. Which may affect the power quality and system stability. Future research should also consider more complex power flow scenarios to design their controllers [112].

VIII. Conclusion

This paper presents a systematic technical review of AC Microgrids functionalities of communication-less primary and secondary control layers. In the primary layer, the droop-based active and reactive power-sharing techniques are studied. Furthermore, their advantages and limitations are also reported. On the other hand, the use of communication issues like latency, data drop-up, and higher implementation costs, in the secondary layer for voltage and frequency restoration are mentioned. To avoid communication and implement robust control principles, techniques involving decentralized voltage magnitude and frequency restoration are reviewed. The techniques are classified and summarized based on certain constraints like considering source dynamics, line impedance, and load dynamics. Finally, future research directions are discussed to improvise the reviewed communication-less primary and secondary control techniques.

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