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# Towards Grid of Microgrids: Seamless Transition between Grid-Connected and Islanded Modes of Operation

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*(Invited Paper)*

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**ABSTRACT** With the ever-increasing number of blackouts in distribution systems arising from a variety of natural and manmade disasters, the frequent and necessary isolation/reconnection of loads without power deviations/fluctuations has become an important issue. Grid of microgrids (MG)s is a promising solution towards a highly resilient and efficient power grid operation. To facilitate this implementation, seamless transition with the utility grid is a key feature the today's MG control needs to possess. This transition ability is of great prominence, especially after the accelerated adaptation of distributed renewable energy sources (RES) in MGs. This ability of the MGs should ensure uninterrupted energy services to critical loads and infrastructures. Thus, the implementation of MG control strategies to enable smooth transition between grid-connected (GC) and islanded (IS) operation modes is mandatory. The control scheme implemented should therefore be capable of mitigating the stirring voltage/current deviations due to frequency/phase misalignment during the transition process. This paper provides an overview of the various MG control schemes that enable seamless transition between GC and IS modes of operation. The main purpose of this paper is to provide a generic overview of the challenges and existing techniques available in literature to mitigate the voltage and frequency (*V-f*) fluctuations at the MG's point of common coupling (PCC) and that of the utility grid; during the transition process. It aims at motivating the development of advanced control schemes in this area of MG related research.

**INDEX TERMS** Grid of microgrids, seamless transition, dual mode inverters, droop control, stability, hierarchical control, grid synchronization.

## I. INTRODUCTION

Microgrids (MG)s have attracted enormous attention in the past few decades due to their easy integration to distributed energy resources (DER)s along with their ability to accommodate high penetration of renewable energy sources (RES)s [1]–[4]. According to the definition adopted by the U.S. Department of Energy and several European agencies, the MG refers to a cluster of interconnected loads, DERs, and energy storage systems (ESS)s which are regulated by a control unit and can act as an independent entity with respect to the power grid [5]. A basic grid interactive MG is as illustrated in Fig. 1.

MGs play a key role in enhancing the grid resiliency and reliability of the distribution system along with enabling high penetration of DERs. The inclusion of DERs in power generation under a regulated dispatch environment can significantly enhance the energy utilization efficiencies, reactive power support and voltage-frequency (*V-f*) regulation, etc.

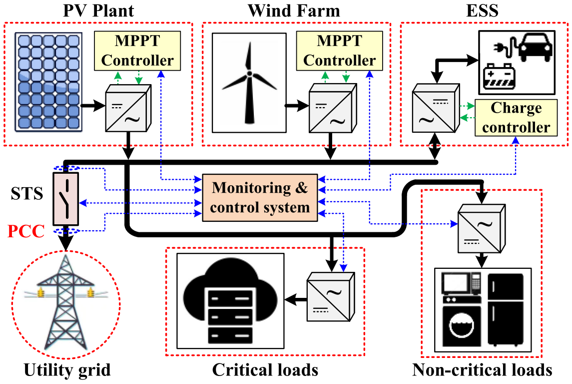


**FIGURE 1.** Basic control structure of a MG.

**TABLE 1.** Voltage and Frequency Trip times specified in IEEE 1547 and IEC 61727 Standards [8–10]

| IEEE 1547 | | IEC 61727 | |
|---|---|---|---|
| Voltage Range (% of base voltage) | Trip Time (s) | Voltage Range (%) | Trip Time (s) |
| $V < 50$ | 0.16 | $V < 50$ | 0.10 |
| $50 \leq V < 88$ | 2.00 | $50 \leq V < 85$ | 2.00 |
| $110 < V < 120$ | 1.00 | $110 < V < 135$ | 2.00 |
| $V \geq 120$ | 0.16 | $V \geq 135$ | 0.05 |

| Frequency range (Hz) | Trip Time (s) | Frequency range (Hz) | Trip Time (s) |
|---|---|---|---|
| $f < 59.3$ or $f > 60.5$ | 0.16 | $f < 49$ or $f > 51$ | 0.20 |

A direct and unsupervised incorporation of a fleet of inverters into the power grid may however compromise the grid stability. This is encountered especially when the inverters' operating point fluctuates with the ambient conditions [3], [4], [6]. These stability issues can be mitigated by forming a grid of MGs and governing their operation using hierarchical control and energy management schemes. Under normal MG operations in grid-connected (GC) mode, the inverters deliver maximum available power to the grid along with other ancillary services such as reactive power support [3]. Here, these inverters are configured to operate in current controlled mode (CCM) and they follow the voltage references at the point of common coupling (PCC). The MG's stability in this case is cohesively regulated by the various sources in the distribution network [7], [8]. In the event of a grid fault, the fleet of inverters in the MG should disconnect upon fault detection. The fault detection times for inverters (or the MG) corresponding to abnormal grid *V-f* are discussed in [8] and have been laid out by the IEEE 1547 [9] and IEC 61727 [10] standards; specified in Table 1. However during these faults, the critical loads in the MG will also be disconnected from the utility grid, leading to interruption in their supplied power. Hence, the main challenge in attaining seamless transition can be paraphrased as related to securing the critical loads with uninterruptible power which is drawn from the neighboring inverters during the transition process.

A potential solution to ensure energy services for critical loads in MGs during a grid fault is to seamlessly transit between GC and islanded (IS) modes of operation as discussed in [11]. In islanded mode, the power converters transit to the grid forming voltage controlled mode (VCM) and participate in catering the needs of the loads to maintain the *V-f* stability; when the static transfer switch (STS) shown in Fig. 1 is opened. This enables the connected MG to smoothly disconnect from the utility grid at the PCC and transit to IS mode of operation. This power support ensures immunity of the critical loads to power interruptions and grid faults caused during the event of natural disasters [12].

The main challenges that arise in seamless transition of a MG between GC and IS modes discussed in [13], [14] include:

1) Frequency fluctuations leading to disturbance in the DER's power angle which affects the MG stability.
2) Large deviations in the DER interfaced inverter output voltage/current due to switching of its operating mode.

To address these issues, various control schemes have been proposed in literature. They can be broadly classified into two types: (a) control schemes for individual inverters and (b) control schemes for entire MG. For both applications, the most commonly used control strategies that facilitate seamless transition are droop control based. They offer advantages such as plug-n-play feature, communication-free power sharing and improved reliability. However, the traditional droop control has some limitations [13], such as:

1) *V-f* deviations in IS mode.
2) unregulated power injection in GC mode.
3) inaccurate reactive power sharing in IS mode.
4) Need of a central synchronization control unit before reconnection.

Various modified droop control schemes are proposed to address these issues which are discussed in the following sections. Seamless transition techniques that use ESSs are impressive alternatives and have gained popularity due to their ability to provide improved power backup, reliability and exceptional performance in MG operation [15]–[17]. These schemes typically follow a master-slave configuration. During GC operation, the MG interfacing inverters operate in CCM, regulating the grid injected current. In IS mode, the ESS interfaced inverter takes over as the master and operates in grid forming VCM while all other inverters are configured as slaves. This master unit is responsible for regulating the *V-f* across the loads while other DER interfaced converters continue to operate in grid feeding CCM; supplying constant P-Q with new '*V-f*' operating points obtained from the MG master [15], [18]. The drawbacks of these control schemes are that the master DER which is typically the ESS, should have higher capacity and power rating which increases the implementation and maintenance cost. Also, all transients in the MG need to be compensated by the master DER that increases the stresses on this DER. Besides, failure of the master DER can cause the entire MG to shutdown [17].

The objective of this paper is to provide a comprehensive overview of the challenges associated with the smooth

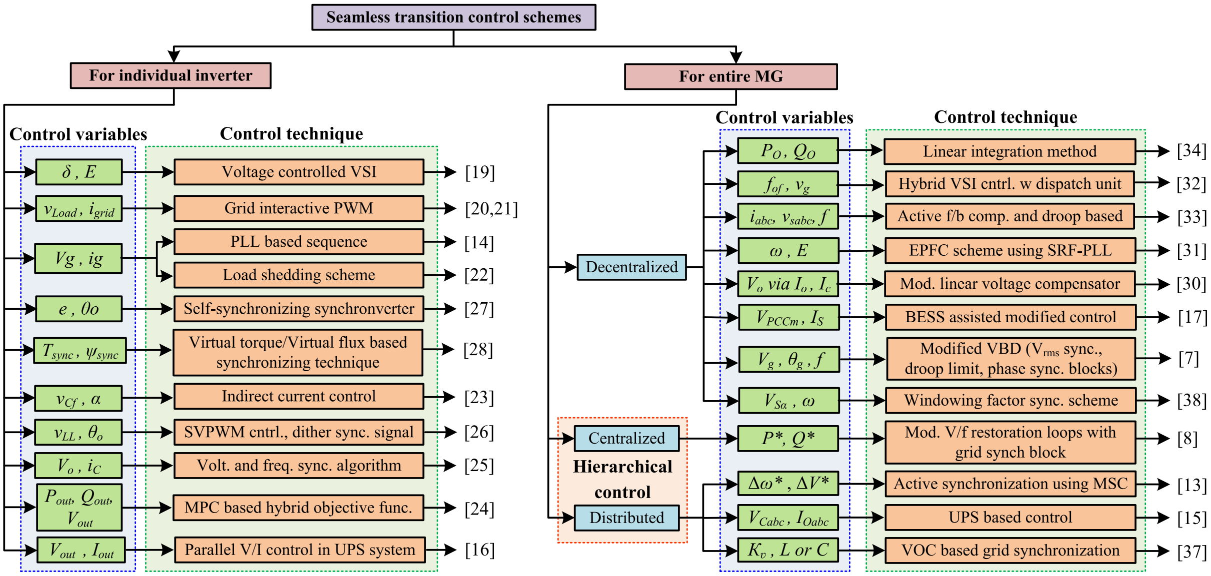


**FIGURE 2.** Summary of different control approaches for attaining seamless transition on single inverter as well as on MG level.

transition of MGs and a comparative analysis of the existing solutions; as classified in Fig. 2. The presented technology review also discusses some of the technical challenges the industry faces today as we move towards implementation of a grid of MGs. The main motivation for this work is to provide a brief summarization of the existing control schemes that support seamless transition and suggest potential gaps for improvements along with providing a basis to explore new research horizons. Initially, various control theories proposed for seamless transition in GC inverters have been discussed in Section II. Next, Section III presents the different control schemes proposed in literature to attain seamless transition in MGs. This section is further sub-classified into decentralized, centralized and distributed control schemes proposed to attain seamless transition in MGs. Section IV presents a roadmap to open research areas which motivate researchers to advance the development of control schemes towards resilient inverters/MGs. Finally, Section V concludes the paper.

## II. CLASSIFICATION OF CONTOL SCHEMES FOR DUAL-MODE OPERATION OF SINGLE INVERTER

Early researches on seamless transition were done with the intention of isolating individual inverters during a fault. A seamless transition control for a voltage controlled voltage source inverter (VC-VSI) was introduced by Gao *et al.* in [19] where *V-f* regulation loops are implemented in the primary control that can operate in GC and IS modes and switch between these modes smoothly. The transition from GC to IS mode involves detection of grid voltage drop by the islanding detection algorithm. Then the integral gain '$K_Q$' of the voltage restoration loop is set to zero; after the STS is opened. This brings the PCC voltage to the nominal value and the inverter can now start operating in islanded mode enabling smooth disconnection. Upon grid recovery, a PLL block tracks the PCC voltage amplitude, frequency and phase to achieve synchronization before initiating reconnection to the grid. This scheme however causes stability issues when implemented on multiple inverters connected in parallel which arises due to lack of co-ordination between the neighboring units.

Another early work on smooth transition of GC inverters was reported by Tirumala *et al.* in [20] where line interactive inverters were suggested for providing uninterrupted power to local loads in the event of a grid fault. The proposed algorithm turns off the STS upon fault detection and monitors the load voltage's magnitude and phase to switch the inverter to VC-VSI mode as the switch current drops to zero. Upon fault clearance, the synchronization algorithm is triggered where initially the inverter reference voltage is ramped up or down to match the load voltage amplitude with the grid voltage. Next, a hysteresis function driven phase synchronization block matches the load voltage phase with the grid phase; by increasing/ decreasing the load voltage frequency. After successful synchronization, the inverter is shifted to CCM and the switch is turned on to realize seamless transition to GC mode. The drawback of this scheme is the large load voltage deviations due to current and load dependence; in addition to requirement of multiple sensors. A solution to these large voltage deviations is suggested by Manuel *et al.* in [21], where a notch voltage-sag compensator uses two capacitors to minimize the voltage fluctuations during the transition process. If the fault occurs in the positive half cycle, the positive charged capacitor is connected to the load while for a fault arising in negative half cycle, the negative charged capacitor is connected and discharged in the load; thereby holding the PCC voltage constant. The drawback here is the need of extra capacitor components.

Other control schemes to mitigate the frequency disturbances or phase jumps during the transition process have been proposed in [14, 22–28]. A transition strategy involving load shedding to recover the inverter voltage was suggested by Balaguer*et al.* in [22]. In GC mode, the inverter operates to provide optimum power to the power grid; based on energy availability, energy cost, etc. Here, the power difference between the generation and the load demand is compensated by the grid. As a grid fault occurs, the inverter disconnects from the grid and continue to inject the preset power to the load leading to a mismatch between the power generation and demand. This causes a *V-f* drift in the operating point of the islanded inverter which needs to be compensated to restore the load voltage before reconnection. The restoration is achieved by the proposed intelligent load shedding technique in which an estimated part of the local non-critical load is disconnected according to a predefined priority which helps to steer the power system from potential instability. As the grid fault gets cleared, the inverter is operated in the synchronous island mode until both the systems are synchronized. The synchronization algorithm estimates the phase difference ‘$\theta$’ between the grid and the load voltage by taking two sets of voltage measurements. Then, the sine of the phase difference ‘$\sin\theta$’ is determined which leads to the estimation of the new phase angle ‘$\theta_{new}$’ for which the inverter and grid voltages are synchronized. Once the load voltage is synchronized with the grid, the switch is closed and the controller transits to CCM before transitioning to GC mode. However, it has been verified that the load voltage and grid current still have significant oscillations during the transition operation. Besides, this technique requires the disconnection of non-critical loads, which degrades the overall system capacity and reliability.

In [14], a modified phase locked loop (PLL) has been proposed to realize seamless transition for three phase GC inverters. A dq-based PLL is used to synchronize the load voltage’s phase with that of the grid in the reconnection mode and to generate a phase of desired frequency in IS mode. Upon detection of a grid voltage sag, an operating sequence involving the PLL operation is initiated to enable smooth transfer to IS mode; while maintaining a stable voltage across the critical loads. However, if the magnitude and phase of the load voltage are adjusted at the same time, the load voltage and grid side inductor current get distorted during the synchronization process. Hence, first the load voltage’s phase is synchronized with the grid voltage following which the voltage magnitudes are matched. This makes the technique slower in attaining its seamless transition objective. Besides, this approach uses two distinct controllers for GC and IS modes which makes the controller implementation complex. All the schemes discussed so far have inherent drawbacks due to the use of linear controllers. Over the past decade, there has been a push towards the use of non-linear controllers in the field of MG control.

Recent trends in MG control with respect to seamless transition have been towards developing faster, advanced PLL or PLL-less solutions to attain grid synchronization. Also, special emphasis has been given on moving away from the conventional droop based power sharing controls in the multi-agent DER environment. These include deployment of control schemes based on concepts such as self-synchronizing synchronverter, virtual synchronous generator, virtual oscillator control, etc. Each concept finds its own applications and has its own set of advantages and limitations over the other as discussed further. In [27], a self-synchronizing synchronverter has been proposed which does not require a dedicated synchronization unit. Synchronverters are inverters that mimic the response of synchronous generators and provide a mechanism for power systems to regulate renewable energy integration in the grid. They automatically synchronize with the grid prior to reconnection and track the grid frequency after transitioning to GC mode. However, this scheme requires an additional operation mode detection mechanism and has slower response due to synchronization delay. Besides, it has reactive power imbalance issues when implemented on parallel inverters and hence does not support truly plug-n-play feature.

To address the above drawbacks, Ramezani *et al.* in [28] have modified the synchronverter control in [27] and proposed a hybrid controller for virtual synchronous generators. Here, an integrated virtual torque (VT) and virtual flux (VFL) linkage based synchronization technique has been proposed that enables seamless transition between islanded and GC modes to provide a true plug-n-play functionality to the synchronverters. The VT term in the proposed control, minimizes the frequency/phase difference between the inverter output voltage and the ac bus/grid voltage by providing a synchronizing torque command ‘$T_{sync}$’ to the frequency control loop. This reduces the overshoots in the inverter output power during the transition process. Similarly, the load voltage amplitude is matched to the ac bus or the grid voltage amplitude by providing a synchronizing virtual flux command ‘$\psi_{\mathrm{sync}}$’ to the voltage control loop; thereby minimizing the overshoot in the output reactive powers. The set of VT and VFL relations for the transition from GC to IS mode of operation are given by (1) and (2).

$$T_{sync} = K_{\varphi}(\upsilon_{o_d}\upsilon_{b_q} - \upsilon_{b_d}\upsilon_{o_q}) = K_{\varphi}\left[-V_oV_b\sin(\delta_o - \delta_b)\right] \tag{1}$$

$$\psi_{\mathrm{sync}} = K_{\psi}(\upsilon_{o_q} - \upsilon_{b_q}) = K_{\psi}\left[V_b - V_o\cos(\delta_o - \delta_b)\right] \tag{2}$$

Here, ‘$K_{\varphi}$’ and ‘$K_{\psi}$’ represents the positive synchronizing VT and VFL gains respectively; while ‘$V_o$’ and ‘$V_b$’ are the inverter output voltage and ac bus voltage amplitudes. ‘$\delta_o$’ and ‘$\delta_b$’ are the ac-bus voltage phase and inverter output voltage phase respectively. The same set of synchronizing torque command ‘$T_{sync}$’ and flux command ‘$\psi_{\mathrm{sync}}$’ relations are applicable for the synchronverters’ transition from IS to GC mode and are given by (3) and (4).

$$T_{sync} = K_{\varphi}(\upsilon_{b_d}\upsilon_{g_q} - \upsilon_{b_q}\upsilon_{g_d}) = K_{\varphi}\left[-V_bV_g\sin(\delta_b - \delta_g)\right] \tag{3}$$

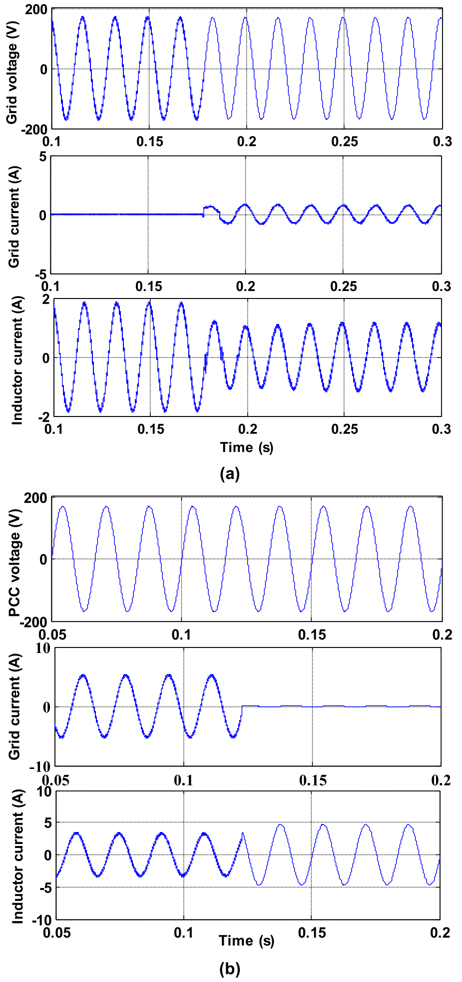
$$\psi_{\mathrm{sync}} = K_{\psi}(\upsilon_{b_q} - \upsilon_{g_q}) = K_{\psi}\left[V_g - V_b\cos(\delta_b - \delta_g)\right] \tag{4}$$

Again here, ‘$K_{\varphi}$’ and ‘$K_{\psi}$’ are the positive synchronizing VT and VFL gains respectively; while ‘$V_b$’ and ‘$V_g$’ are the ac bus voltage and grid voltage amplitudes respectively. '$\delta_b$' and '$\delta_g$' are the ac-bus voltage phase and grid phase respectively. The use of same set of governing relations for GC as well as IS operation modes eliminates the need of controller reconfiguration; thereby facilitating seamless transition.

Another seamless transition strategy for a single phase grid interactive inverter has been proposed by Kim *et al.* in [23] where the voltage and current transients encountered during change of controller are reduced by regulating the inverter output current's peak value using the inner voltage loop. The inverter current '$I_O$' fed to the grid is indirectly regulated by controlling the filter capacitor voltage '$V_{Cf}$' and its phase angle '$\alpha$' with respect to the grid voltage '$V_s$'. This is attained by the outer PI controller which slowly minimizes the error in '$I_O$' by regulating '$\alpha$' that is added to the phase angle of '$V_s$' produced by a PLL circuit to generate the filter capacitor voltage reference '$V_{CF}^*$'. If the grid is in fault, the control angle '$\alpha$' reaches its maximum value '$\alpha_{max}$' thereby making the resultant reference phase angle as '$\alpha_{max} + \theta$'. If the peak value of '$V_{CF}^*$' generated using this phase does not lie within the window range of the grid voltage, the inverter is disconnected from the grid and it starts operating in islanded mode. When the grid voltage is restored, the control angle '$\alpha$' is reduced slowly by the PI controller to regulate the filter capacitor voltage '$V_{Cf}$'. Once the filter capacitor voltage and the filter inductor current '$I_O$' are regulated at the nominal value, synchronization is achieved and the inverter can then be reconnected to the grid seamlessly. The drawback of this method is that since the peak value of the filter inductor current determines the grid current reference, this reference can have inaccurate instantaneous value during the transition process.

Li *et al.* in [25], have proposed a controller with inner voltage-current control loops and external active-reactive power control loops along with additional synchronization control to attain seamless transition. Synchronization is achieved by adding two separate synchronization compensators to the real and reactive power control loops. The magnitude '$\Delta E$' and phase '$\Delta\delta$' errors of the voltage phasors at both ends of the STS are fed as inputs to the synchronization compensators and their outputs are fed to the real and reactive power control loops. This makes the microgrid voltage phasor follow the grid voltage phasor in magnitude and frequency and attain synchronization of the microgrid with the utility grid. Upon successful synchronization and after closing the STS, the synchronization compensators are deactivated by setting their outputs to zero so as to not affect the operation of the real and reactive power control loops in the GC mode. The main drawback of this control scheme is that the dynamics of the power control are fixed by droop control and are not easily changeable. Besides, this system is highly susceptible to output short circuit and other network faults.

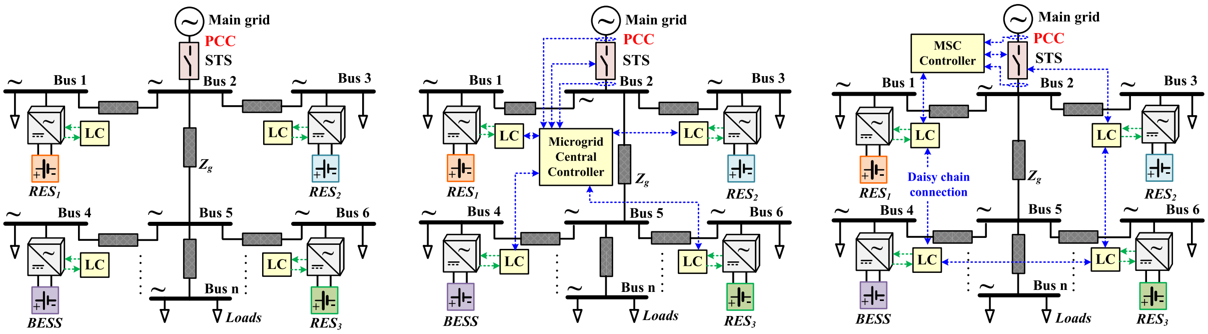
The authors of [24] have proposed a model predictive control (MPC) based control scheme for a grid-tied single phase VSI that supports seamless transition between GC and IS modes of operation. Under normal operation when the grid fails, the controller detects islanding and operates in islanding mode. A synchronization algorithm tracks the phase angle and grid voltage magnitude to provide a load voltage reference that is utilized in IS mode of operation. During reconnection, the phase difference between the grid voltage and the load voltage is detected by the phase adjustment algorithm. Next, the load voltage frequency is smoothly adjusted to track the grid voltage during the transition process. A simplified simulation was carried out to test the performance of this dual mode inverter for transitions between GC and IS modes. Fig. 3(a) and (b) show the performance of the dual mode inverter during the transition from IS to GC modes and from GC to IS modes respectively. In Fig. 3(a), the system operates in IS mode initially and at t = 0.178 s, the system is connected to the grid. The filter inductor current and the grid current profiles do not show fluctuations indicating a smooth reconnection of the inverter system with the grid. In Fig. 3(b), the system initially operates in GC mode and at t = 0.123 s, a grid fault occurs and the system is disconnected from the grid. The PCC voltage and the filter inductor current profiles show a smooth transition of the inverter to IS mode as the grid current falls to



(a)

(b)

**FIGURE 3. Performance of the model predictive control based scheme proposed in [24] during transitions from (a) islanded mode to grid-connected mode; and (b) grid-connected to islanded mode.**



(a) Decentralized control scheme (b) Centralized control scheme (c) Distributed control scheme

**FIGURE 4.** Different control schemes applied in ac MGs to attain seamless transition (LC: Local controller).

zero. The main advantage of this technique is the fast response of the controller due to the inherent nature of model predictive control. However, the performance of this scheme for grid connected multiple inverters has not been analyzed yet.

With respect to the use of ESS for seamless transition, a scheme using line-interactive UPS systems has been reported by Okui *et al.* in [16], where voltage and current controllers execute in parallel in order to attain a smooth mode change. Here, the ESS interfaced converter along with a momentary abnormal voltage detection (MAVD) circuit helps in regulating the *V-f* deviations across the local loads during a grid fault. Under a fault condition, the voltage and current control systems along with the MAVD and the power failure detection circuit ensure that the power fed to the critical load remain regulated. In the initial stage, the power to the load is provided by the dc side capacitor in the power converter as far as the power fluctuations lie within the tolerance band. If the grid fault continues, the ESS's dc-dc converter will move into discharge mode and start feeding power to the load. Also, the voltage and current controllers detect the grid as soon as it becomes available and the input current is increased gradually so that the UPS system does not affect the dynamics of the diesel generator. However, here the UPS units are not analyzed for autonomous operation under parallel connection of multiple units.

The above discussion considers seamless transition only on individual inverter level; achieved using primary control loops. However in practice, MGs typically consist of multiple inverters connected at various buses. Hence, it is crucial to consider the interactions of the different inverter controllers while investigating seamless transition in MGs [29]–[31]. Besides, in a multi-agent environment of connected DERs, the *V-f* set-points of the MG are agreed upon by all the participating inverters following the droop control norms [8], [29]. During the transition of a MG, the voltage magnitude, frequency and power angle; defined by the power sharing between various DERs undergo deviations. Thus, the seamless transition objectives can be achieved if these magnitude and phase deviations are regulated within tolerable limits. The control schemes that offer seamless transition on a MG level are discussed in the following section.

## III. CONTROL SCHEMES FOR DUAL-MODE OPERATION OF MICROGRIDS

This section emphasizes on discussing the control schemes that enable seamless transition on a MG level. They are classified mainly into three major categories (a) decentralized control (b) centralized control and (c) distributed control schemes. The connection topologies for these control schemes are illustrated in Fig. 4(a)-(c). They differ typically in the topology of their controller implementation; as discussed in the following sub-sections.

### A. DECENTRALIZED CONTROL SCHEMES

Most of decentralized MG control schemes that are capable of attaining seamless transition are droop based. Their network topology is shown in Fig. 4(a). Along with providing proportional active-reactive power sharing, these schemes do not require dedicated high bandwidth (BW) communication (except for synchronization purposes) and can control MGs in GC, IS modes and during mode transitions [32]–[34]. In [34], a decentralized droop based strategy for seamless transition of two inverters using low BW communication has been proposed. Here, the MG's *V-f* at the PCC is regulated by adjusting the active and reactive power references for the two inverters. The proposed linear integration method uses minimal communication to exchange the power reference set points between the controllers and attains synchronization with the utility grid. A typical droop control driven grid-tied inverter is as shown in Fig. 5. Its control consists of the inner voltage and current control loops and the outer droop (power) control loop. Seamless transition is attained here by regulating '$V_i$-$\omega_i$' operating point by adjusting the active power '$P_O$' and reactive power '$Q_O$' set point values in the droop relations given by (5) and (6) below.

$$\omega_i = \omega_O - m_i(P - P_O) \tag{5}$$

$$V_i = V_O - n_i(Q - Q_O) \tag{6}$$

Here, '$\omega_O$', '$V_O$', '$P$' and '$Q$' represent the nominal frequency, nominal voltage, average active and reactive powers of the VSI based $i^{th}$ DER respectively, while '$m_i$' and '$n_i$' are the droop co-efficients. Fig. 6(a) illustrates the deviation in '$\omega$'

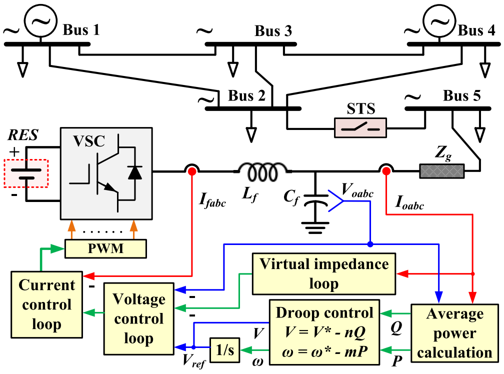


**FIGURE 5.** **A typical droop controlled DER-interfaced grid tied inverter.**

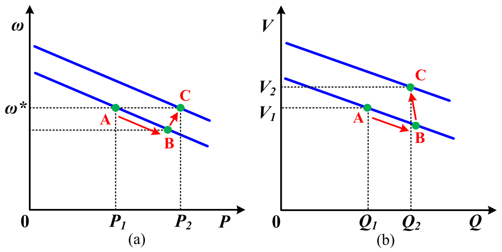


**FIGURE 6.** **(a) Increase in P causes drop in $\omega$ and (b) Increase in Q causes drop in V; compensated by droop control by moving to point C.**

as the active power demand '$P_i$' changes. Similarly, Fig. 6(b) illustrates the deviation in grid voltage '$V$' from '$V_1$' (at no load) to '$V_2$' with variations in reactive power '$Q_i$' demand. However, in order to restore the MG *V-f* to attain seamless reconnection at other than the rated load conditions, this scheme has to drift the P and Q operating points from their nominal values thereby resulting in power mismatches during reconnection [17].

The above issue is addressed in the modified versions of droop control schemes discussed below. In the decentralized control scheme proposed in [32], one of the DERs is elected as a dispatch unit and it provides the deficient power during the mode transitions when moving from GC to IS mode; thus compensating for the *V-f* fluctuations. Under normal operations in GC mode, the dispatch unit continues to operate in droop mode and delivers power proportional to the difference in the offset frequency and the grid frequency. However, the dispatch unit is also solely responsible to compensate for the power losses during the transition process, thereby introducing the drawback of reduced system reliability. In [33], another decentralized double loop droop control scheme was proposed where the seamless transition between modes was attained by adjusting the coefficients of the power droop defined in the outer power loop; thereby ensuring accurate power sharing. A hybrid droop control strategy has been proposed in [35] called hybrid polar–vector control, which combines the features of droop based control and self-synchronized synchronverter control to achieve seamless transition. The controllers can function for different operating conditions without the need of reconfiguration and also provide the plug-n-play functionality. Here, the power sharing is realized in IS mode by the angle and frequency loops while in GC mode they provide required damping and synchronization. The design of the MG controller is complicated nonetheless.

The highlighting features of droop based control schemes lies in their low reliance on communication for synchronization, which also mitigates the single point of failure issue. However, the droop control schemes struggle to maintain a constant power flow in GC mode, due to strong coupling between $\omega - P$ and $V - Q$ along with the grid *V-f* fluctuations. Besides, the droop control $\omega - P$ and $V - Q$ relations work efficiently in GC mode only when the X/R ratio of the distribution lines is much larger than 1. As the MG transits to IS mode, the X/R ratio of the interconnecting lines approaches less than or equal to unity. This significantly impacts the droop power sharing relations and increases the coupling between active and reactive power; thus degrading the performance of the controllers [36]. The authors of [31] have attempted to address these issues by proposing an enhanced power flow control (EPFC) scheme where the feedforward of grid frequency and voltage magnitude is used to mitigate the impacts of grid fluctuations on power flow. Also, a voltage magnitude control is proposed to improve the control accuracy. If the *V-f* magnitude exceeds the specified limits, the reference points obtained from the synchronous reference frame PLL are reverted to the original rated values '$\omega_O$' and '$E_O$'; thus ensuring a smooth transition between the GC and IS modes. Another modified droop-based linear voltage compensator for power converters forming the MG, has been proposed in [30]. Here, the scheme includes a) a voltage controller with capacitor current feedback input to the voltage controller and output current feedforward to input current control; b) a modified droop control that emulates the inertia response of a synchronous generator. The additional capacitor current feedback in the voltage control loop provides additional damping needed to mitigate the voltage deviations. Similarly, the output current feed-forward as input to the current controller helps to minimize the disturbances on the output voltage.

Despite all the above modifications, the droop control still needs time-scale separation from the voltage controllers by at least an order of magnitude; so as to maintain the system stability [37]. This makes the droop control inherently slow in response. Various control schemes for MG control that use non-linear control such as virtual oscillator control (VOC) [37] or those using dispatch units such as ESS [17], [38], [39] provide solution to this problem and are discussed below.

The authors of [17] have proposed a decentralized modified power control technique which uses an ESS to attain seamless transition. Here, the DER consisting of PV and battery ESS (BESS) acts as the MG master and controls the STS. Each residence has local loads and slave DERs consisting of local batteries interfaced via voltage source converters (VSC). When a grid fault occurs, the BESS governing master controller opens the STS and switches itself from power control mode

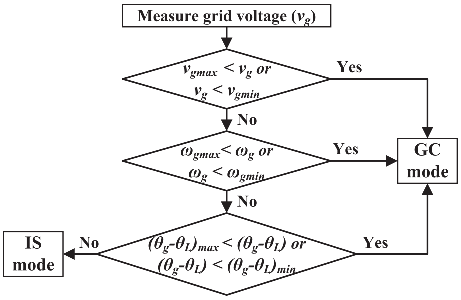


**FIGURE 7.** **Windowing factor based grid synchronizing control [38].**

(PCM) to VCM mode. In this mode, the master controller regulates the MG voltage at a reference amplitude and the grid reference frequency. The instantaneous reference phase angle value is obtained from the previous estimated value obtained in GC mode. Upon clearing the grid fault, the master controller resynchronizes the MG voltage with the grid voltage using the grid reference voltage. The reference voltage used by the master controller here is passed through a rate limiter to ensure a smooth transition. Finally, the master controller switches back to PCM and closes the STS to move the MG to GC mode. The limitation of this control scheme is that the capacity of the BESS interfaced to the master converter needs to be at least 150% of the average power demand of the MG [17] and thus leads to relatively expensive implementation. Besides, the batteries' limited lifecycles demand periodic replacements.

In [38], a windowing factor [40] based decentralized control for a PV-BESS based MG has been proposed. It is used to estimate the phase and frequency of the utility grid. The windowing factor based synchronization control estimates the values of load voltage phase '$\theta_L$' and grid voltage phase '$\theta_g$' simultaneously. Upon detection of grid fault, the STS is opened and the control of VSC switches from GC mode to IS mode. The resynchronization process involves detection of voltage amplitude, frequency and phase at the PCC to check if they lie in the desired operating range as illustrated in the flowchart in Fig. 7. The corresponding VSC parameters are then matched with that of the grid until the conditions are satisfied and the STS is closed. The VSC's controller then switches back to GC mode. The transfer function for voltage, frequency and phase estimation of sensed signal is given by (7) and (8).

$$\frac{\upsilon_{s\alpha}}{\upsilon_s} = \frac{[\omega_1(s)G_1 i_{L2}]/s}{1+[\omega_1(s)G_1 i_{L2}]/s} \tag{7}$$

$$\frac{\theta_g}{Input\ of\ \omega\ section} = \frac{[\omega_2(s)G_2\omega_{r1}]/s+[\omega_3(s)G_3\omega_{r2}]/s}{1+[\omega_2(s)G_2\omega_{r1}]/s+[\omega_3(s)G_3\omega_{r2}]/s} \tag{8}$$

Here, '$\upsilon_{s\alpha}$' and '$\upsilon_s$' are the estimated and the actual values of PCC voltage respectively. '$\omega$ ' and '$\theta_g$' are the estimated grid frequency and phase angle values while '$G_1$', '$G_2$' and '$G_3$' are the set gain values. '$\omega_1(s)$' is the window factor for voltage magnitude estimation while '$\omega_2(s)$' and '$\omega_3(s)$' are window factors for estimating the grid frequency and phase values. Appropriate values for window lengths and gains provides accurate estimation of grid *V-f* and phase. A simplified simulation was carried out to assess the performance of this windowing factor based control scheme for transitions between GC and IS modes. Figs. 8(a)-(b) show the performance of the proposed system during the transition from IS to GC modes and from GC to IS modes respectively. In Fig. 8(a), the system operates in IS mode initially and at t = 0.169 s, the system is commanded to transition to GC mode. The grid current and the inductor current profiles show that the system synchronizes with the grid within 0.02 s. In Fig. 8(b), the system initially operates in GC mode while at t = 0.12 s, a PCC voltage sag occurs thereby triggering a grid fault and the system is disconnected from the grid. The PCC voltage and the filter inductor current profiles show a momentary dip which gets cleared in less than 0.02 s and the system goes

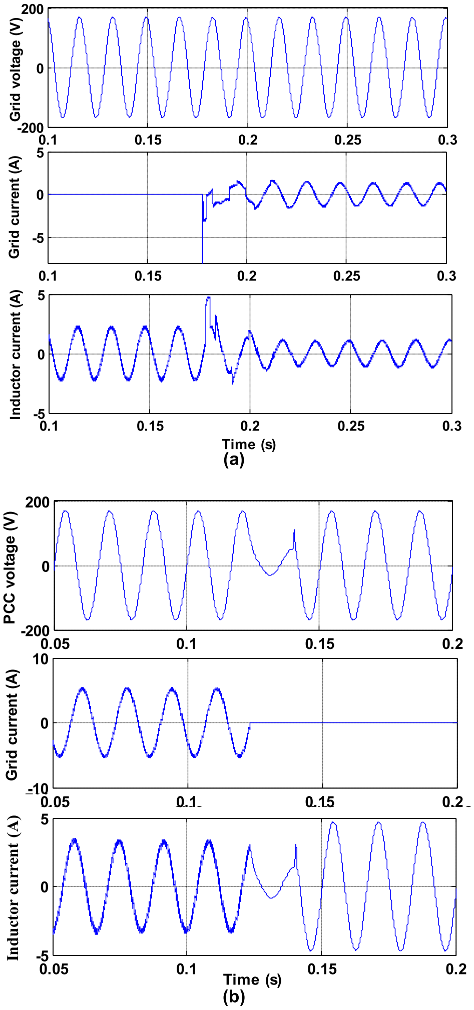


**FIGURE 8.** **Performance of the windowing factor based decentralized control scheme proposed in [38] during transitions from (a) islanded mode to grid-connected mode; and (b) grid-connected to islanded mode.**

into IS mode. This scheme does not use PLL for synchronization and hence the frequency transients and phase jump issues dominant in PLL-based estimators are avoided [38]. However, the controller design is highly sensitive to the values of window factors and gains.

Typically, most of the control schemes utilizing UPS systems assign the UPS unit as the MG master which has to regulate the PCC in IS modes [17]. In contrast to the PLL based schemes [38], the modified UPS based control schemes improve the transient response of the MG to sudden grid fluctuations; thereby enabling a smooth transition.

### B. CENTRALIZED CONTROL SCHEMES

The centralized type of MG control schemes typically deploy hierarchical control architectures which have been standardized for MG control due to their advantages such as accurate power sharing, low voltage ride through capabilities, etc. as discussed in [36], [41]–[44]. They distribute the control into three layers: primary, secondary and tertiary control. Each control layer is responsible for attaining specific target(s) and works with different execution rates [45]. The primary layer is implemented in the LC, as evident in Fig. 4(b). It is responsible for power sharing and employs droop based or similar control schemes. Secondary control is centrally located and is responsible for restoring the *V-f* deviations caused by the primary control. It warrants uninterrupted voltage to the local loads; while meeting the seamless transition criteria. The tertiary controller is also centrally located and is responsible for monitoring the power interaction between the MG and the grid. It also monitors the grid status and sends control updates to regulate the active-reactive power fed to the grid; in addition to MG *V-f* alignment with the power grid for smooth transitions.

In [8], a centralized control based seamless transfer strategy for a single phase MG is presented. The MG consists of voltage controlled VSI (VC-VSI) and current controlled VSI (CC-VSI) working together; for both GC and IS modes of operation. The GC and IS operation mode control loops are combined into one droop based control which forms the primary controller for each VC-VSI. This facilitates seamless transition since there is no need of changing the primary controllers. The secondary control is implemented on the MG central controller (MGCC) unit which acts as the central controller and has direct communication access to each inverter and STS. The STS monitors the *V-f* of the MG PCC voltage and the grid voltage and opens the switch if it finds irregularities in the grid voltage. It also transmits magnitude and frequency updates to MGCC periodically. Using these signals, the MGCC sends updated P-Q set points to all the inverters to regulate the MG's PCC voltage. The droop control functions that are used to realize this voltage regulation and to enable the inverter to operate in either modes of operation are given by (9) and (10) below.

$$\theta = \theta^* - (m_d + (m/s))(P - P^*) \tag{9}$$

$$V = V^* - \ (sn_d + n + (n_i/s))(Q - Q^*) \tag{10}$$

where, $\theta^* = \ \omega^*/s$ is the output voltage phase angle, '$m$' and '$n$' are the $P - \omega$ and $Q - V$ droop gains respectively. '$P^*$' and '$Q^*$' are the inverter's real and reactive output power demands in GC mode. As the grid recovers, the STS updates the MGCC which in turns triggers the voltage and modified frequency restoration loops (including the grid synch block) to synchronize the MG voltage at the PCC with the grid voltage. A PLL is used to determine the *V-f* at the PCC. The grid synch block adds a frequency deviation term '$\omega_{synch}$' to the MG frequency to minimize the phase error between the grid voltage and the MG voltage and thereby enabling a seamless reconnection to the gird. However, this scheme suffers from the single point of failure issue, since the failure of the MGCC or any of the communication link(s) can cause the entire MG to collapse. Also, this scheme lays large computational burden on the MGCC which makes the design complex [44]. These issues can be addressed by using distributed control schemes discussed below.

### C. DISTRIBUTED CONTROL SCHEMES

The distributed control schemes have been developed to harness the advantages of decentralized and centralized control schemes [13], [37], [44], [46], [47]. These schemes require only local peer-to-peer connections realized using sparse distributed communication links as evident in the network topology given by Fig. 4(c). Various distributed control schemes for MG control have been proposed in literature [13], [37], [47]. In addition to the reduced communication dependency and improved resiliency, decentralized control schemes also possess advanced features such as ability to eliminate the static errors that arise in multi-agent systems as analyzed in [47]. Hou *et al.* in [13] proposed a distributed hierarchical control scheme that can provide seamless transition feature in ac MGs. In contrast to [8], this scheme uses a distributed secondary control layer using a leader-follower consensus protocol and a tertiary mode supervisory control (MSC). The primary control layer is droop based. The MSC is placed around the STS and transmits compensation signals to only a few leader DERs located near the STS. They exchange these signals with all other connected DERs using the sparse communication network. In case, the power quality of the utility grid does not meet the operation criteria, the STS is opened and grid transitions to IS mode. When the grid fault is cleared, the MG *V-f* and phase need to be synced with that of the utility grid. Here, the frequency synchronization is achieved using the *P-ω* droop relation given by (11). The *P-ω* droop characteristics curve for the i^th^ DER is illustrated in Fig. 9(a).

$$\omega_i = \omega^* - m_i P_i + \Delta\omega_i \tag{11}$$

$$k_\omega \frac{d\Delta\omega_i}{dt} = \sum_{j \in N, j \neq i} a_{ij}(\Delta w_j - \Delta w_i) + \gamma_i(\Delta\omega^* - \Delta\omega_i) \tag{12}$$

The term '$\Delta\omega_i$' is the secondary control's frequency regulation term contributed in the primary droop control and is defined by (12). '$a_{ij}$' indicates the existence of a data link

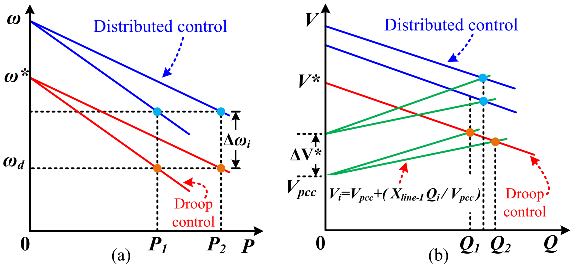


**FIGURE 9.** **Droop characteristics with *V-f* restoration loops (a) P-$\omega$ restoration and (b) Reactive power sharing with PCC voltage (Q-V) restoration.**

connection between $i^{th}$ and $j^{th}$ DER and will be set to '1' if the link actually exists. If the link fails or the $j^{th}$ DER is shut down, '$a_{ij}$' will be set to '0' thereby making the contribution of the $j^{th}$ DER in the frequency regulation process equal to zero. The term '$\gamma_i$' is set to '1' if $i^{th}$ DER is a leader; for all other $i^{th}$ non-leader DERs this parameter is set to '0'. '$k_\omega$' is a positive control gain. Similarly, the voltage synchronization is achieved using the *Q-V* droop relation given by (13). The *Q-V* droop characteristics curve is illustrated in Fig. 9(b).

$$V_i = V^* - n_i Q_i + \Delta V_i + \beta_i \Delta V^* \tag{13}$$

$$k_v \frac{d\Delta V_i}{dt} = \sum_{j\in N, J\neq i} b_{ij}(k_{Qj}Q_j - k_{Qi}Q_i) \tag{14}$$

Here, '$\Delta V_i$' is the secondary control's voltage regulation term defined in (14). Similar to (12), here '$b_{ij}$' indicates the existence of a data link connection between the $i^{th}$and $j^{th}$ DER and will be set to '1' if the connection exists. If the link fails or the $j^{th}$ DER is shut down, '$b_{ij}$' will be set to '0' thereby neglecting the contribution of the $j^{th}$ DER in the voltage regulation process. The term '$\beta_i$' represents leader mode and is set to '1' if $i^{th}$ DER is a leader and for all other non-leader DERs, this parameter is set to '0'. The terms '$\Delta V^*$' and '$\Delta\omega^*$' in (13) and (12) are the active synchronization compensation signals for the MG PCC voltage amplitude and frequency respectively and are transmitted by the MSC to all the DERs. These compensation signals steer the $V - \omega$ operating point of all the connected DERs so as to match the MG's *V-f* with that of the utility grid. Once synchronization is successfully achieved, the STS is closed and the MG smoothly transitions into GC mode. The advantage of using the MSC with spare communication is that the single point of failure issue is mitigated and features such as plug-n-play and link failure resiliency are appended in the MG control [36], [45].

In [15], another hierarchical distributed control based scheme for a MGs interfaced to a line interactive UPS system has been proposed. Under normal operation, the STS is closed and the UPS can export or import power from the grid to charge the batteries. The MSC that controls the STS, measures the power at PCC, gets updates about the batteries' State of charge (SoC) from the UPS system and sends droop regulated active-reactive power update commands to other DER units via a low bandwidth communication. When a grid fault occurs, the embedded anti-islanding control in each DER's controller sets their PCC *V-f* to an upper or lower limit. The MSC detects this operating point adjustment as a fault and opens the STS switch to transition into IS mode. It also sends a status update to all DER units. The UPS system regulates the MG voltage at the PCC according to the power references received from the MSC using the modified droop relations given by (15) and (16) below.

In GC mode, when the UPS is charging the dc link of the UPS system is maintained by the dc/ac converter while the buck converter charges the battery. As a grid fault occurs and before the STS detects it, the direction of power flow in the UPS reverses due to loss of stiffness in the PCC voltage. Thus power starts flowing from dc link capacitor to the ac loads. This causes drop in dc link voltage which is detected by the dc/dc controller and it switches to boost mode. It then starts regulating the dc link voltage while the dc/ac converter regulates the PCC voltage. Thus a smooth transition is facilitated by the cascaded converters in the UPS system during disconnection. Once the grid is restored, the STS monitors the MG's PCC and main grid voltage. It closes itself when both signals are in phase thereby attaining smooth reconnection. It also sends an update signal to the UPS system. The *V-f* regulation is achieved by using the modified droop relations in the primary control of each DER; given by (15) and (16). Here, $P^*$ and $Q^*$ values are obtained from the MSC which is responsible for attaining synchronization before transitioning to GC mode. These values are passed through a rate limiting block to provide smooth reconnection.

$$\omega = \omega_0^* - [k_\omega + (k_{\omega\_I}/S)](P - P^*) \tag{15}$$

$$V = V_0^* - [k_\alpha + (k_{\alpha\_I}/S)](Q - Q^*) \tag{16}$$

Here, '$\omega_0^*$', '$V_0^*$', '$k_\omega$' and '$k_\alpha$' are the nominal frequency and nominal voltage reference values, proportional frequency coefficient and proportional voltage drooping coefficients respectively. '$P^*$' and '$Q^*$' are the power flow controller active and reactive power references that are adjusted to ensure '$\omega - V$' regulation. Also, '$k_{\omega\_I}$' and '$k_{\alpha\_I}$' are the integral-frequency and voltage drooping coefficient set to zero in IS mode and are used to ensure accurate power tracking in the GC mode.

Awal *et al.* in [37] have proposed another distributed hierarchical control synchronization scheme for VOC based MGs. The VOC based inverters exhibit fast synchronization of their outputs by providing improved damping response during transients [37], [48]. However, the VOC's non-linear nature makes the design of secondary control layer quite complicated. The authors address this issue by proposing a compatible hierarchical control structure that uses the VOC based secondary control layer and tertiary level for power reference tracking. The proposed controller can provide improved MG operation and is capable of seamless transition between IS and GC modes. VOCs are based on the Van der Pol oscillator theory discussed in [49] and are characterized by time domain equations given by (17) and (18).

$$L\,{}^{di_L}/_{dt} = {}^{\upsilon}/_{k_\upsilon} \tag{17}$$

$$C\left({}^{d\upsilon}/_{dt}\right) = -\alpha\left({}^{\upsilon^3}/_{k_\upsilon^2}\right) + \sigma\upsilon - k_\upsilon i_L - k_\upsilon k_i i \tag{18}$$

Here, '$L$' and '$C$' represent the virtual oscillator model inductance and capacitor values respectively [50]. '$k_\upsilon$' represents the scaling factor for the voltage regulation control. '$\alpha$' is a positive constant related to the cubic voltage dependent current source while '$\sigma$' represents the negative conductance element in the VOC model. The detailed design of these model parameters lie outside the scope of this work and an in-depth analysis is available in [49], [50]. The instantaneous modulation index '$m$' for the next period is obtained by discretizing and evaluating (19) and (20) in time domain to get the instantaneous oscillator voltage '$\upsilon$'. The proposed controller combines the voltage tracking closed loops with the primary real–reactive power sharing layer.

A relay is placed at the PCC to regulate the STS switch. In IS mode, this relay senses the voltage on both ends of the STS to determine the phase and amplitude errors and accordingly sends a signal to close the STS after successful synchronization. Before initiating transition to GC mode, the relay generates reference amplitude '$V^*$' and phase '$\theta^*$' which are obtained by running a PLL on the grid voltage '$\upsilon_g$'. The VOC based secondary control uses these reference signals to match the amplitude and phase of the MG voltage to that of the utility grid and minimize the error. This mode of the VOC operation is called the grid-synchronization mode. In IS mode, the same VOC controller also attains *V-f* regulation to the nominal values. This eliminates the need of control switching during transition between GC and IS modes. The voltage regulation at secondary layer is achieved by dynamically adjusting the scaling factor '$k_\upsilon$' through '$u_\upsilon$' in (19) below. The voltage error, $e_\upsilon = (V^* - V_{pcc})$ is used to determine '$u_\upsilon$'.

$$u_\upsilon = (K_p^\upsilon + K_i^\upsilon/S)e_\upsilon;\quad k_\upsilon = k_{\upsilon 0} + u_\upsilon \tag{19}$$

Here, '$K_p^\upsilon$' and '$K_i^\upsilon$' are the proportional and integral gains of the voltage regulation loop controller. Similarly, phase and frequency regulation is achieved by dynamically modulating the nominal frequency '$\omega^*$' to minimize phase error given by $e_\theta = (\theta^* - \theta_{pcc})$. '$\theta_{pcc}$' is obtained from the PLL. The term '$u_\theta$' is obtained from '$e_\theta$' and dynamically modifies the inductor '$L$' or capacitor '$C$' in the VOC network [50] by using (20).

$$u_\theta = (K_p^\theta + K_i^\theta/s)e_\theta;\ C = C_0 + u_\theta \tag{20}$$

Here, '$K_p^\theta$' and '$K_i^\theta$' are the proportional and integral gains of the phase loop while '$C_0$' is set as per design guidelines [50]. On convergence of secondary control loops to steady state, the conditions in (21) are verified and STS is closed.

$$\left|rms(\upsilon_g) - rms(\upsilon_{pcc})\right| \le \varepsilon_V \text{ and } \left|ph(\upsilon_g) - ph(\upsilon_{pcc})\right| \le \varepsilon_\theta \tag{21}$$

Here, '$\varepsilon_\upsilon$' and '$\varepsilon_\theta$' are the predefined thresholds for acceptable voltage and phase deviations respectively. This ensures seamless transition operation in the VOC based MGs. Although, the VOC based control offers faster convergence, the fast variation in the primary response of VOC controlled part of the MG can impact the overall stability of the MG.

Based on the above discussion, it can be inferred that distributed control schemes offer the most optimal performance for MG control with respect to seamless transition from GC to IS as well as IS to GC modes. However, each scheme has its own set of advantages/drawbacks as mentioned in the Tables 2 & 3 above and hence the choice of control scheme solely depends on the application needs. A comparison summary of the various types of MG control schemes, namely: decentralized, centralized and distributed control, with respect to various performance metrics is provided in the Table 4.

## IV. FUTURE RESEARCH ROADMAP IN DUAL-MODE OPERATING MICROGRIDS

This section discusses the current trends and research areas in MG control along with seamless transition feature; which primarily focus on improving the MG resiliency. In addition to the advanced concepts such as virtual synchronous machine control [28], virtual oscillator control [37], model predictive control [24] and windowing factor based synchronization [38], [40]; various researches are being conducted to develop innovative control schemes for MGs. These include incorporation of state-of-the-art features such as delta power reserve [7], [51], [52], electric springs [53]–[55], loads as energy assets [56], state machine based control algorithms [57] etc. to facilitate seamless transition in MGs. This will result in simplified controller implementations, size reduction in the energy storage requirement, power quality enhancement and reduced stress on the MG controllers. In [55], the authors discuss mitigation of V-f fluctuations in a MG using electric springs, which has been adapted to fit the seamless transition requirements and thereby minimize or even eliminate the need of ESSs in MGs.

Research emphasis has also been placed by government agencies towards development of highly resilient community MGs. The idea here is to develop a community MG that encompasses feeder-level MGs having multiple points of common coupling (MPCC) with neighboring MGs and the entire distribution grid [58]. This concept will involve estimation of optimal islanding boundaries so as to detect the location of optimal MPCC to minimize the transient behavior anticipated at these MPCCs during the transition of the MG between GC and IS modes.

DC grids offer potential advantages in terms of operational efficiency, ease of scalability, easy DER integration, etc. However, the current power distribution system lacks the ability to immediately transition to a DC grid and hence require a hybrid AC/DC MG. Thus, interconnection of ac and dc MGs to form hybrid MGs with improved system response is another current trend in MG research [59]–[62]. These hybrid MGs provide numerous advantages such as improved efficiencies,

**TABLE 2. Advantages/Disadvantages of Various Techniques to Attain Seamless Transition in Single Inverters**

| Control scheme | Features / Advantages | Drawbacks / Disadvantages |
|---|---|---|
| Voltage controlled VSI based [19] | • Supports transition between GC and IS modes.<br>• Inherent islanding detection capability.<br>• Fault ride through capability in GC mode. | • Instability issues in IS mode due to reactive power loop.<br>• Lack of co-ordination with other DERs causes instability. |
| Grid interactive PWM [20] | • Applicable to utility interactive single phase inverters.<br>• Provide uninterrupted power to local loads on grid failure.<br>• Simple implementation. | • Large voltage/current (V/I) spikes during transitions.<br>• Requires multiple sensors; hence expensive.<br>• Slower in response. |
| Notch voltage sag compensator [21] | • Compensates the V/I spikes encountered in [20].<br>• Uses positive and negative cycle capacitors.<br>• Maintains power level across loads during transitions. | • Additional capacitors and circuitry needed.<br>• Complex and expensive implementation. |
| Load shedding Scheme [22] | • A modified technique to implement GC and IS mode operation.<br>• Load shedding algorithm to attain intentional islanding.<br>• Resynchronization algorithm for grid reconnection. | • Large oscillations in output voltage and grid current during reconnection.<br>• Disconnection of non-critical loads reduces system capacity and reliability. |
| PLL based sequence [14] | • PLL synchronizes load and grid voltage phases.<br>• In IS mode, PLL generates the reference phase. | • Load voltage's phase and magnitude need to be matched separately to avoid distortions.<br>• System response degrades significantly under unbalanced and distorted grid voltage conditions.<br>• Complex implementation of PLL. |
| Self-synchronizing synchronverter [27] | • Does not require a dedicated PLL for synchronization.<br>• Has improved performance and complexity.<br>• Reduced computational burden. | • Slower in response due to need of synchronizing time.<br>• Requires new configuration during transition to GC and IS modes of operation.<br>• Reactive power imbalance issue in parallel inverters. |
| VT and VFL based synchronization [28] | • Simple and effective phase and voltage amplitude synchronization technique for synchronverters.<br>• Unified synchronizing technique enables plug-n-play. | • Tuning of synchronizing controller is extremely sensitive to gain values.<br>• Slower response due to inherent property of synchronverter. |
| Indirect current control [23] | • Inner voltage loop regulates output current in both modes.<br>• Unified controller facilitating simpler implementation. | • Grid current can have dc offsets or inaccurate values during mode transitions between GC and IS modes. |
| Voltage and frequency sync. algorithm [25] | • A unified controller that regulates output voltage to resynchronize MG with utility grid voltage in both modes.<br>• Faster response since no switching of controller needed. | • Dynamics of the power control are fixed by droop control and cannot be modified.<br>• Based on voltage control strategy which is susceptible to output short circuits and network faults. |
| MPC based hybrid objective function [24] | • Non-linear control facilitating fast response to fluctuations.<br>• Smooth disconnection /reconnection due to use of grid synchronization and phase adjustment algorithms.<br>• No PLL required for synchronization. | • Mismatches between the model fed values and actual values of filter components (L and C) significantly affects the system performance. |
| Parallel V/I control in UPS system [18] | • Parallel operating voltage and current controllers to attain seamless transition.<br>• BESS along with the MAVD circuit regulates the voltage across local loads. | • The UPS system cannot operate autonomously in parallel with other DER units.<br>• UPS cannot be implemented to form a MG. |

reduced power losses, easy integration to RESs, simplified control schemes, etc. [61], [62]. However, not much work with regards to seamless transition in hybrid MGs has been carried out; which can be an interesting research kickoff. Further, various enhanced control schemes for ESS coupled hybrid MGs are proposed [62]and can be adapted to incorporate seamless transition capabilities. Power electronics based smart transformer has been incorporated in MGs to regulate the power demand-response balance in GC mode [63], [64]. The smart transformer can provide seamless disconnection/ reconnection with the utility grid and continue providing uninterrupted power to local loads during grid faults [63]. Besides, numerous researches have been carried out in the development of coordinated control strategies for smart transformers to facilitate efficient monitoring, coordination, control management, and economic dispatch of the interfaced DERs and loads in a MG [65].

On the contrary, the high incorporation of low inertia DERs in the conventional grid has also raised protection related concerns and hence new protection schemes that are compatible with the MG architecture need to be developed. Some MG protection schemes have been discussed in [66]–[68]. In [66], an overcurrent (OC) relay based protection co-ordination scheme for dual mode operating MGs has been proposed to minimize the overall relay operating time for critical primary and backup operations. Other potential opportunities for MG

**TABLE 3. Advantages/Disadvantages of Various Techniques to Attain Seamless Transition in MGs**

| **Decentralized schemes** | **Features / Advantages** | **Drawbacks / Disadvantages** |
|---|---|---|
| Linear integration method [34] | • $V$-$f$ regulated by adjusting power references in the droop characteristics.<br>• Sparse communication needed to attain synchronization. | • Attaining synchronization at other than rated load conditions leads to power mismatches.<br>• Accurate $V$-$f$ tracking not achieved.<br>• Low power quality due to slower controller response. |
| Hybrid VSI control with dispatch unit [32] | • Dispatch unit provides the deficient power during transition.<br>• No communication required to regulate power flow between inverters.<br>• Improved power quality. | • Dispatch unit is solely responsible to compensate for power losses during transition.<br>• Increased stresses on the dispatch unit.<br>• System reliability is low. |
| Active f/b compensation and droop based [33] | • A double loop droop control where seamless transition is attained by adjusting the droop coefficients of the power loop.<br>• Unified controllers and power circuit for GC and IS modes.<br>• Can regulate dispatchable as well as non-dispatchable units. | • Power loop introduces small deviations in the MG $V$-$f$ which cause large mismatches in low power systems.<br>• The controller has slower response to transients; thereby affecting the power quality across loads. |
| Hybrid polar vector control [35] | • Angle and frequency loops provide power sharing in IS mode and provide damping and synchronization in GC mode.<br>• Unified controller for GC and IS operation modes.<br>• Combines droop and self-synchronizing synchronverter features to provide seamless transition function. | • Complex implementation.<br>• Highly sensitive to system parameters.<br>• Struggles to maintain constant power flow in GC mode. |
| EPFC scheme using SRF-PLL [31] | • Feedforward of grid frequency and voltage magnitude used to regulate power flow in GC mode.<br>• Voltage magnitude control improves control accuracy. | • Performance is very sensitive to sudden change in voltage phase and may lead to instability.<br>• Controller design is critical due to feedforward terms. |
| Modified linear voltage compensator [30] | • Suppresses voltage, current and frequency transients and provides seamless transition.<br>• Improved dynamic performance by providing more damping.<br>• Easier in implementation. | • Feedforward terms can impact system stability.<br>• Sensitive to design parameters. |
| BESS assisted modified control [17] | • Master DER (PV+ BESS) controls STS and regulates MG voltage in IS mode and during reconnection.<br>• Slave DERs draw constant active power from the grid.<br>• High power quality across loads. | • Large capacity of BESS required.<br>• Expensive implementation and maintenance. |
| Window factor based sync. control [38] | • No PLL used for grid phase synchronization.<br>• Frequency transients and phase jump issues are avoided.<br>• Improved reliability and performance flexibility. | • Design of controller highly sensitive to values of window factors and gains. |

| **Centralized hierarchical schemes** | **Features / Advantages** | **Drawbacks / Disadvantages** |
|---|---|---|
| Mod. $V$-$f$ restoration loops with grid synch block [8] | • Unified controller to enable seamless transition between GC and IS modes of operation.<br>• MGCC centrally manages the operation of the MG.<br>• Accurate power sharing and $V$-$f$ regulation achieved. | • Requires high bandwidth communication with DERs.<br>• MGCC's single point of failure issue.<br>• Large computational burden on MGCC makes system design complex. |

| **Distributed hierarchical schemes** | **Features / Advantages** | **Drawbacks / Disadvantages** |
|---|---|---|
| Active synchronization using MSC [13] | • Addresses the issues of [11] by using a distributed sparse communication based architecture.<br>• Reduced processing burden on the MSC.<br>• Features such as plug-n-play and link failure resiliency. | • Synchronization with MSC requires longer due to sparse communication.<br>• Compromise between system response time and data transfer capacity of the communication channel. |
| UPS based control [15] | • Sparse communication link required to share STS status.<br>• Embedded anti-islanding controllers in each DER indicate grid fault which is then recognized by the UPS controller.<br>• High power quality across local loads. | • Expensive implementation.<br>• High stresses on the UPS unit.<br>• Failure of UPS unit can compromise the MG stability. |
| VOC based grid synchronization [37] | • Faster convergence and synchronization.<br>• Improved damping response during transients.<br>• Unified controller implementation enables easier transition between GC and IS modes | • Design of higher layer controllers is very tedious.<br>• Fast variation in VOC controller response can impact the entire MG stability.<br>• Controller design highly sensitive to gain values. |

**TABLE 4.** Comparison of Types of MG Control Strategies With Respect to Different Performance Metrics

| Performance metric | Decentralized control schemes | Centralized control schemes | Distributed control schemes |
|---|---|---|---|
| Synchronization dependency | Primary control layer | Secondary and Tertiary control layer | Secondary control layer |
| Synchronization time | Long | Short | Intermediate |
| Power quality | Poor | High | Moderate |
| Communication dependence | Not required | High | Low |
| Power sharing | Poor | High | Moderate |
| Controller reconfiguration requirement | No | Yes, with addition/removal of DER | No |

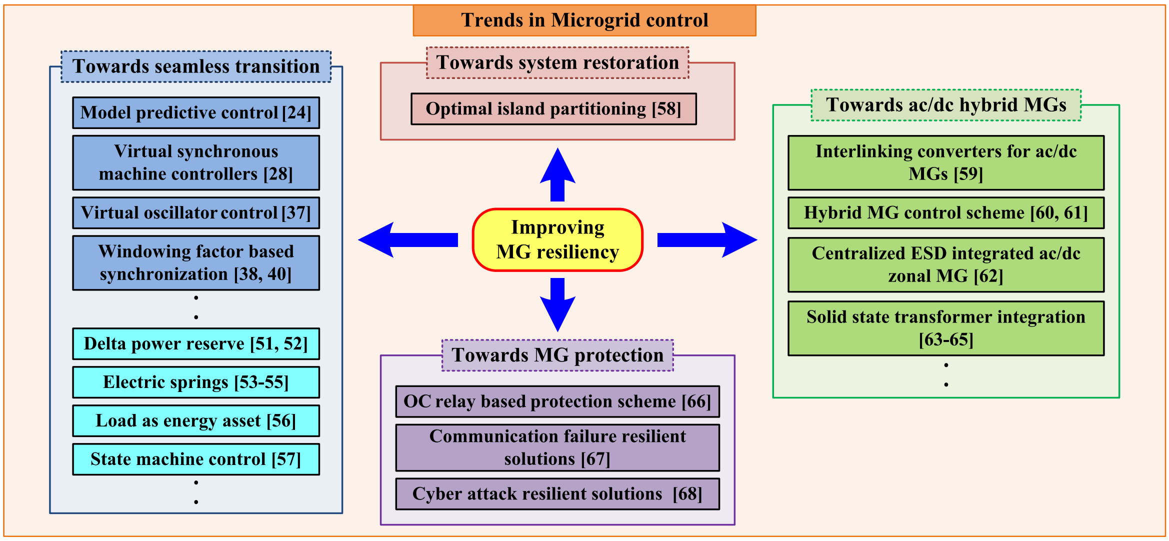


**FIGURE 10.** Research roadmap towards resilient Microgrids.

research can include investigating the MG resiliency to communication failures [67] and cyberattacks [68] and developing control schemes to address these anomalies. The above discussed trends and future research directions in the field of MG control schemes are summarized in the Fig. 10.

## V. CONCLUSION

This paper presents an extensive review on the challenges encountered in the seamless transition of a MG between GC and IS modes. An assessment of the various proposed control schemes to address these issues has been carried out. Under the canopy of this classification, different control schemes proposed for seamless transition of individual inverters are discussed. Next, the need to evaluate seamless transition on a MG level in a multi-agent DER environment been deliberated. A detailed classification on the control schemes to attain seamless transition on MG level has then been presented. These schemes are sub-classified into decentralized, centralized and distributed control schemes. Alongside, variations of these schemes involving use of ESS, VOC, etc. have also been studied. Each scheme exhibits its own sets of advantages and weaknesses. Finally, a brief account on current trends and future research in MG control has been presented. The sole motivation behind this work is to provide researchers with a promising direction towards future research areas in MG control to develop advanced synchronization and control schemes. These directions are aimed towards facilitating the development of a highly resilient next generation grid of MGs.

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