IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received August 7, 2020, accepted August 28, 2020, date of publication September 1, 2020, date of current version September 15, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3020965

On Grid-Interactive Smart Inverters: Features and Advancements

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This work was supported in part by the Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy Technologies Office, under Award DE-EE0008767, and in part by the Kansas State University Open Access Publishing Fund.

ABSTRACT Traditionally, a grid-interactive inverter providing ancillary services is called a smart inverter. However, broader features will be required for the next generation of inverters that can be categorized as self-governing, self-adapting, self-security, and self-healing. For grid-interactive inverters, the self-governing feature can be identified as the capability of inverters to operate in grid-following and grid-forming control modes, where the self-adapting is referred to as more flexibility realized by adaptive controllers for stable dynamics of inverters under various grid conditions. Moreover, for supervisory control and economic dispatch in a grid with high-penetration of inverter-based power generators, a minimum communication might be necessary, but it can place grid-interactive inverters in danger of being hacked when self-security becomes essential to identify malicious setpoints. Furthermore, the self-healing is defined as fault-tolerance and stress reduction under abnormal conditions. It suggests that after realizing these features, an inverter is called a smart inverter. In this paper, the advancements toward achieving these features for grid-interactive inverters are reviewed.

INDEX TERMS Smart inverters, self-security, self-adapting, self-governing, self-healing, cyberattacks.

I. INTRODUCTION

The energy infrastructure is rapidly changing as more sustainable energy resources such as photovoltaic arrays, wind turbines, and energy storage systems are distributed within the grid as power generation units. The power generation from these intermittent dc and ac sources requires solid-state converters as the interface between the energy resources and the power grid. These converters typically contain multiple stages, including an inverter as the grid-side stage. However, these multi-stage converters are simply known as grid-interactive inverters, and decentralized generation units are called distributed generators (DGs). The high-penetration of DGs provides more flexibility for power systems, where inverters play the most significant role in DGs. An inverter with the capability to make proactive and autonomous decisions based on local measurements and external data can be defined as a smart inverter. Fig. 1 illustrates the desired features of a smart inverter. For example, inverters can be programmed to provide ancillary services for power grids under abnormal conditions to improve power quality. This mode of operation for inverters is referred to as grid-supporting mode [1], [2]. Inverters can also operate in grid-forming mode to form an islanded microgrid following a blackout caused by natural disasters, etc. [3]–[8]. Furthermore, inverters play

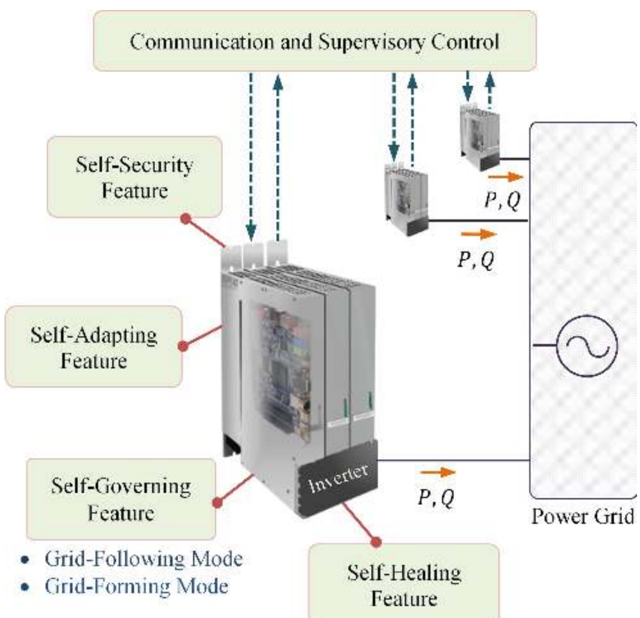


FIGURE 1. Smart inverters connected to the power grid and a cyber network with the features beyond the P and Q grid-feeding duty.

The associate editor coordinating the review of this manuscript and approving it for publication was Ning Kang.

TABLE 1. A classification to define different modes of operation for grid-interactive inverters.

Grid-Following	Current Source (P, Q- Controlled)	Grid-Feeding		Maximum power tracking and constant (typically zero) reactive power injection
		Grid-Supporting	Smart	Ancillary services (voltage regulation, etc.) added to the basic features
Grid-Forming	Voltage Source (V, f- Controlled)			Power sharing, voltage magnitude and frequency control

a significant role in making the capability of clustering a power grid, known as a grid of microgrids or networked microgrids [9].

The high-penetration of DGs has many benefits but brings new security, stability, and reliability challenges in power systems. For example, although decentralized control schemes, e.g., droop controllers, can address the power-sharing between DGs, the energy management and economic dispatch between DGs cannot be achieved optimally without a form of the supervisory control scheme, which needs a type of communication between a utility operator and inverters [10]–[13]. Thus, a smart inverter becomes a cyber-physical system that includes both physical parts, e.g. modules, sensors, and processors, and data packet communications. The inverters connected to communication or cyber network could be in danger of being hacked, thus jeopardizing the security of the inverters. Furthermore, the inherent zero inertia feature of inverter-based DGs can result in low-inertia microgrids, making the gird vulnerable to sudden disturbances and leading to instability. Inverters can also fail quickly because of internal switch faults, risking the system reliability. Therefore, self-security, self-adapting, and self-healing features are also the desired characteristics of a smart inverter besides the self-governing feature. Finally, for the proper operation of an inverter with different modes of operation, the inverter should be capable of seamlessly switched between modes of operation. In other words, smart inverters should be able to self-govern as communicating with agents or an operator in a supervisory structure. The communication or cyber network provides access to information beyond the available data from their local sensors. The awareness about the situation of other DGs, smart meters, and forecasted data would allow a smart inverter to project anomalies and make proactive decisions.

In the following, each section of this paper discusses one of the smart inverter features, see Fig. 1. Also, recent advancements and existing technical challenges regarding each feature are briefly presented in the following sections.

II. SELF-GOVERNING FEATURE

The self-governing feature is defined as the capability of supporting the grid by providing autonomous ancillary services or forming microgrids and networked microgrids by regulating the grid voltage and frequency. These modes of operation for grid-tied inverters are in contrast with just grid-feeding, in which the maximum available power at unity power factor is injected to the grid, see Table 1.

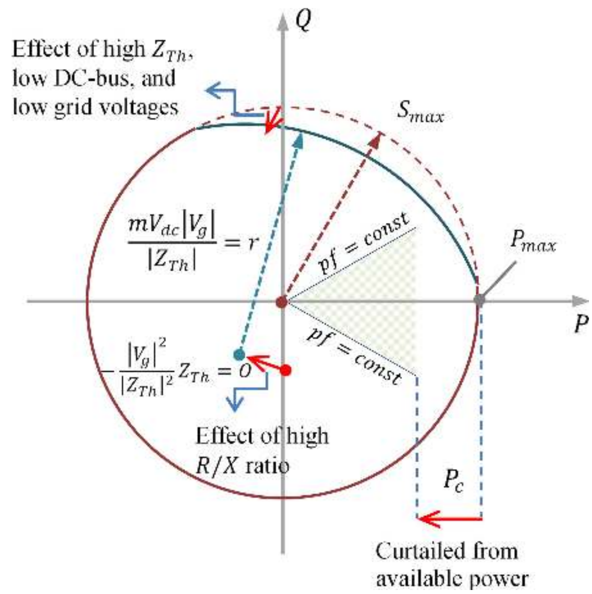


FIGURE 2. Typical operating region of a grid-interactive inverter in a distribution grid with a relatively high Z_{Th} and R/X ratio.

A. GRID-SUPPORTING MODE

Inverters in power grids encounter various abnormal conditions. The most commonly occurring abnormalities are symmetrical and asymmetrical voltage sags. Inverters are required by the utilities to stay connected to the system under voltage sags, which is referred to as low voltage ride-through (LVRT). Smart inverters should have the capability to detect such grid abnormalities, remain connected to the grid, and consequently provide support to the grid, in the form of reactive power support and negative-sequence compensation. In the following subsections, the grid supporting feature is discussed separately for symmetrical and asymmetrical anomalies.

1) GRID-SUPPORTING AND SYMMETRICAL ANOMALIES

Inverters should automatically reduce their active power based on the peak current limit, as shown in Fig. 2, when providing reactive power support [14]–[16]. As the penetration of inverters is increasing, a sudden loss of power from all the inverter-based DGs could result in a more significant issue than the voltage sag itself. Recent standards, e.g., IEEE Std. 1547-2018 [16], require inverters to remain connected to the grid under voltage sags and provide reactive power. However, if the voltage sag persists for too long, the inverter should then be isolated from the grid [16]. The active power injected

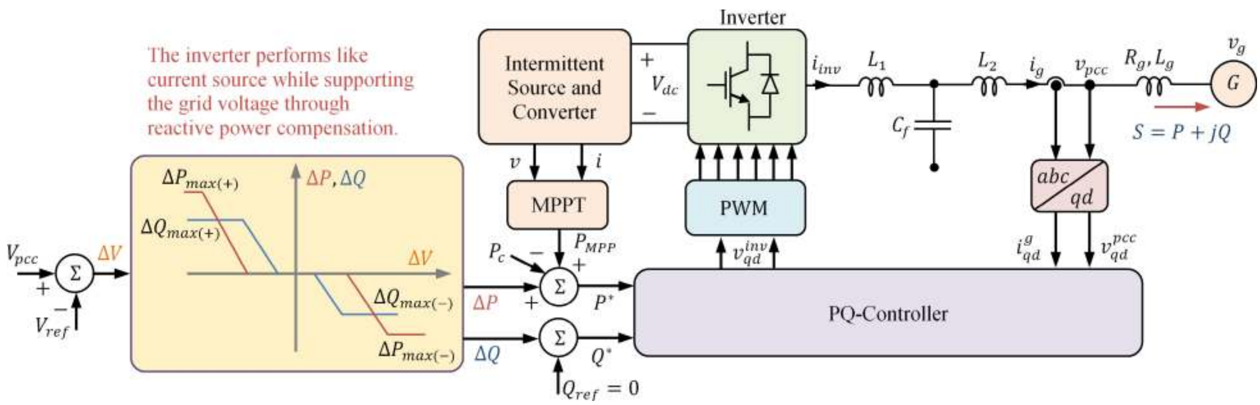


FIGURE 3. Control block diagram of a PQ-controlled grid following (grid-feeding/grid-supporting) inverter.

into the grid should be adjusted as the reactive power is increased to avoid violating the maximum current limit of the inverter, which would otherwise trip the inverter. Along with the maximum current limit, shown as a circle with the radius of S_{max} in Fig. 2, the amount of active and reactive power accessible for the inverter at a specific time depends on the available dc-bus voltage, V_{dc}, the modulation index, m, and the impedance between the inverter and the grid [15], [17], [18]. The second circle with the radius of $mV_{dc}\left|V_g\right| / |Z_{Th}|$ is also shown in Fig. 2. To demonstrate this second circle, one can write the power transferred from the inverter to the grid as follows:

$$S = P + jQ = \frac{k_m V_{dc}\left|V_g\right| e^{-j\delta} - \left|V_g\right|^2}{Z_{Th}^*} \tag{1}$$

where, V_{dc} is the dc-bus voltage, k_m for linear modulation of three-phase inverters is $0.612m$ for sinusoidal-pulse-width-modulation (SPWM), and $0.707m$ for space-vector PWM (SVPWM), when $0 < m \leq 1$, $k_m V_{dc}$ is the line-line rms voltage at the inverter terminals, V_g is the line-line rms voltage of the grid, δ is the angle between the inverter and the grid, and $Z_{Th}^* = |Z_{Th}|\, e^{-j\theta_z}$ is the complex conjugate of the Thevenin equivalent impedance of the grid seen by the inverter, which includes the filter effect. From (1), one can simply write the following equation.

$$\left(P + \frac{\left|V_g\right|^2 \cos(\theta_z)}{|Z_{Th}|}\right)^2 + \left(Q + \frac{\left|V_g\right|^2 \sin(\theta_z)}{|Z_{Th}|}\right)^2 = \left(\frac{k_m V_{dc}\left|V_g\right|}{|Z_{Th}|}\right)^2 \tag{2}$$

where, Eq. (2) demonstrates a circle with the radius of $mV_{dc}\left|V_g\right| / |Z_{Th}|$ and the center of $-\left|V_g\right|^2/Z_{Th}^*$. As depicted in Fig. 2, an increase in the R/X ratio the center of this circle is shifted to the left, and a decrease in the available dc-bus voltage, V_{dc}, or a low grid voltage, V_g, in which Z_{Th} has a relatively high value in weak grids, shrinks the disk identified by the circle. Any change in these parameters can result in intersecting this circle with the S_{max} circle, i.e. $P^2 + Q^2 = S_{max}^2$, and thus, losing part of the normal operating region of an inverter in a weak grid. Being inside S_{max} circle, but outside of the second circle may not necessarily lead to instability unless the inverter feeds a weak grid when the current harmonics can significantly distort the PCC voltage.

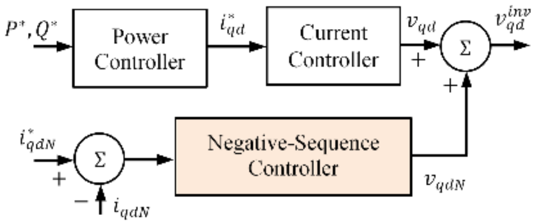
Fig. 3 shows a grid-supporting inverter, which extracts the maximum available power, P_{MPP}, of an intermittent source, e.g. PV arrays, and feeds the grid. Voltage source inverters (VSIs) are commonly employed in DG units, whereas current source inverters (CSIs) can also be applied. Unlike a VSI that is a buck (step-down) converter, i.e. $V_{dc} > V_{LL,rms}$, a CSI is a boost converter [19]–[21], and thus can be fed by a parallel connection of small dc sources, enhancing the reliability and availability of DG units. Regardless of the inverter topology, the maximum power capacity of the inverter must be curtailed to provide a margin, as demonstrated in Fig. 2, for injecting reactive power, and subsequently, a capability to regulate the voltage at PCC, i.e. v_{pcc}. As shown in Fig. 3, the grid-supporting feature can be implemented by adjusting the active and reactive power setpoints using ΔP and ΔQ adjustments through a conventional or hybrid droop control scheme as given below

$$\begin{cases} P^* = P_{MPP} - P_c + \Delta P \\ Q^* = Q_{ref} + \Delta Q \end{cases} \tag{3}$$

where, ΔQ can be formulated as

$$\Delta Q = \begin{cases} (-1/m_Q)\Delta V & |\Delta V| > V_{th} \\ 0 & |\Delta V| \leq V_{th} \end{cases} \tag{4}$$

where, V_{th} is the threshold voltage determined by grid codes, e.g. IEEE Std. 1547, and m_Q is the droop control coefficient. Notice, the output of the droop, ΔQ, must be limited between $\Delta Q_{\max(-)}$ and $\Delta Q_{\max(+)}$, as one can derive from the normal operating region shown in Fig. 2. The active power can similarly be tuned to support the grid, particularly in the distribution power grid, in which R/X ratio is relatively high. The grid-supporting feature is not limited to the voltage support. Inverters can also operate as harmonic and negative sequence compensators in asymmetrical three-phase systems.



Determining i^*_{qdN}	Description
Option 1	Cancel unbalanced current component
Option 2	Cancel active power oscillation
Option 3	Cancel reactive power oscillation

FIGURE 4. Block diagram and decision table for negative-sequence controller in grid-supporting mode.

2) GRID-SUPPORTING AND ASYMMETRICAL ANOMALIES

Asymmetrical anomalies can occur due to asymmetrical faults in the power grid and uneven distribution of single-phase loads in the distribution grid. A smart inverter can support the grid in such instances by providing negative-sequence compensation services on top of the positive-sequence reactive power support [22]–[26].

As shown in Fig. 4, supplementary q- and d-axis current control paths can be inserted to the control scheme for providing negative-sequence compensation to the grid currents, irrespective of whether the control scheme is formulated based on stationary or synchronous reference frames [22]. These paths feed the negative-sequence components of the grid current back to the controller, as shown in Fig. 4, with a zero-reference value to achieve balanced grid currents while the local load might be asymmetrical. However, negative-sequence compensation provided in such a way does not compensate for the negative-sequence component of the voltage at PCC. Therefore, oscillations in the active and reactive power may still remain, which in turn can cause a ripple in the dc-bus voltage of the inverter. The ripples extending beyond the voltage ratings of the capacitor can damage the dc-bus capacitors. The setpoints of the negative-sequence controller can be adjusted to any value other than zero to mitigate some of the oscillations. In general, the desired values of the controller can be set to either mitigate active and reactive power oscillations or compensate unbalanced grid currents [23], see Fig. 4. More control objectives for the negative-sequence controllers have also been proposed in the literature [24], [25]. In [24], the setpoints of the negative-sequence controllers are designed to reduce the negative-sequence component of the voltage at PCC. In [25], the objective of the controllers is to reduce the power oscillation as much as possible while also limiting the currents at their rated values. A smart inverter equipped with a negative-sequence compensation feature should be capable of providing such services based on the appropriate control objective depending on the specific situation. Since the inverter references are unbalanced when providing negative-sequence compensation, some of the references may reach the overmodulation region even at rated power. A low-frequency common-mode signal can be added to the PWM reference signals to keep the inverter in the linear modulation region while providing ancillary services such as negative sequence and harmonic compensations [26].

B. GRID-FORMING MODE

In contrast to a grid-following inverter, a grid-forming inverter operates as a voltage source, see Fig. 5, and Table 1. In a power grid, not all inverters need to work in grid-forming mode [3]–[8]. Generally, inverters powered by non-intermittent sources such as battery energy storage and natural gas microturbines are chosen to be grid-forming inverters, while the remaining inverters can operate in their original mode of operation, e.g. grid-feeding mode. Inverters powered by renewable sources such as PV arrays and wind turbines can also operate in grid-forming mode, but only when they are equipped with their own energy storage units. A grid-forming inverter must be sized for higher-rated values compared to an equivalent grid-feeding inverter to provide sufficient flexibility and a stability margin, particularly in asymmetrical and weak grids.

To form islanded microgrids, and possibly form a grid of these microgrids, smart inverters must optimally share the total load among themselves and other power generation units. The power-sharing and the control of voltage and frequency can be achieved using either centralized or decentralized techniques. The main features of centralized and decentralized techniques are discussed in the following subsections.

1) CENTRALIZED CONTROL TECHNIQUE

In the centralized control approach, inverters adopt a communication based secondary control structure [10]–[13], [27], [28], which can be categorized as master-slave, concentrated, and distributed control techniques. The master-slave and distributed control techniques are explained below.

a: MASTER-SLAVE CONTROL TECHNIQUE

In a master-slave scheme, an inverter operates as a voltage source to regulate voltage magnitude and frequency while other inverters operate as current sources [29], [30]. The inverter that regulates the voltage and frequency is called master-inverter. Master inverters softly start before slave-inverters feed an islanded microgrid. For small microgrids, a single grid-forming or master-inverter is sufficient to regulate the amplitude and frequency of the voltage at the main ac bus. However, for a large microgrid, one inverter would not be able to handle the load variations of the microgrid, and as such, multiple grid-forming or master-inverters might be required. To synchronize the grid-forming inverters, a communication link, which will share the phase and frequency of a reference signal, is required [11], [29], [30]. The master-slave technique provides outstanding power-sharing performance. In the case of tripping the master-inverter, one of the slave-inverters needs to be seamlessly switched to operate as the new master-inverter.

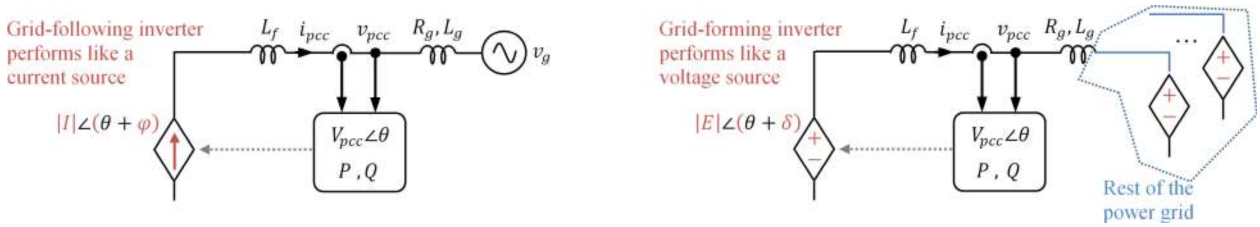


FIGURE 5. Inverters in different modes of operation in grid-following for grid-tied systems, and grid-forming for islanded microgrid systems.

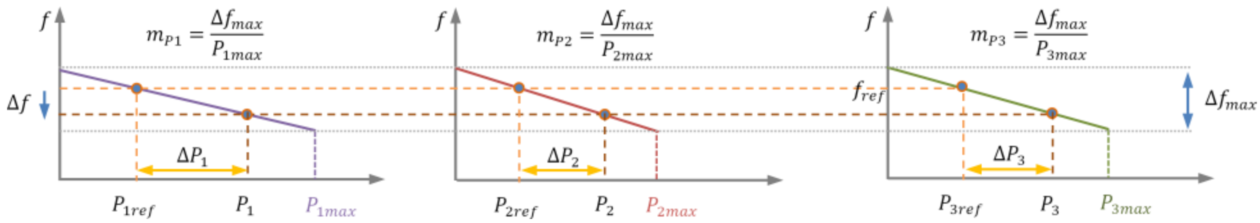


FIGURE 6. A demonstration of power sharing between three inverters with different capacity, P_{imax}, using *P*-*f* droop control technique, these inverters contribute to the load change, ΔP_L, based on their capacities or droop coefficients, m_{Pi}, as $\Delta P_L = \Delta P_1 + \Delta P_2 + \Delta P_3$.

b: DISTRIBUTED CONTROL TECHNIQUE

In a distributed control scheme, each inverter regulates the voltage and frequency of the output voltage based on the grid nominal reference values [11], [27], [28], [30], [31], e.g. 240V, 60Hz; however, those are slightly adjusted based on the average current of all inverters in a microgrid, i.e. for a microgrid with N inverter the average of output currents is given by

$$i_{avg} = \frac{1}{N}\sum_{k=1}^{N} i_{pcc,k} \tag{5}$$

The error of the output current for each inverter with respect to the average current is then calculated as $i_{ek} = i_{avg} - i_{pcc,k}$. The error signal is decomposed into dq frame of reference and used to adjust the frequency and voltage controller [11]. These adjustments can be tuned further to share the total load based on economic dispatch. Like the droop control scheme explained in the next subsection, the frequency and voltage have the flexibility to deviate slightly from their nominal values. The nominal frequency should be restored following the power-sharing stage. Many investigations have been reported on various distributed control methods, for example, a technique in which each inverter needs the data from its local sensors and the information of only nearby DG units to minimize the required communication network [27].

2) DECENTRALIZED CONTROL TECHNIQUE

Two of the most known decentralized control schemes are droop and virtual synchronous generator (VSG) techniques.

a: DROOP CONTROL TECHNIQUE

A droop control scheme provides a decentralized approach, which is inherited from the parallel operation of synchronous generators. The grid-forming inverters equipped by droop controllers do not necessarily require a communication link

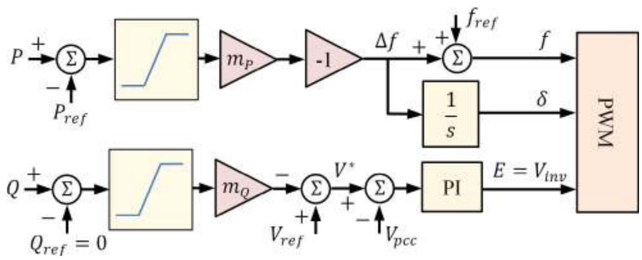


FIGURE 7. A basic block diagram for *P*-*f* and *Q*-*V* droop power sharing.

for power-sharing [11], [31]–[34]. The power-sharing concept using *P*-*f* droop lines is demonstrated in Fig. 6. The control scheme still needs a PI voltage control loop. A basic droop control block diagram is shown in Fig. 7. However, the reference voltage information is generated by the droop equations. The *P*-*f* and *Q*-*V* droop equations can be written as:

$$\begin{cases} \Delta f = -m_{Pi}\Delta P_i & i = 1, 2, \ldots, N \\ \Delta V = -m_{Qi}\Delta Q_i & i = 1, 2, \ldots, N \end{cases} \tag{6}$$

where, m_{Pi} and m_{Qi} are the droop coefficients of the i^{th} inverter, the frequency is given by $f^* = \Delta f + f_{ref}$, and the desired voltage at PCC is obtained from $V^* = \Delta V + V_{ref}$. Notice, for distribution grids and more resistive circuits, *P*-*V*, and *Q*-*f* droop control schemes have demonstrated better power-sharing among the inverters. The former droop equations can still be used in high R/X ratio grids with the addition of virtual inductance/impedance in the control scheme, which makes the output impedance of the inverter more inductive [33]. The amount of power each grid-forming inverter will share can be controlled through its droop coefficient, which is a function of the rating of the inverter, see Fig. 6. Reactive power-sharing can sometimes be challenging using droop control because of the unequal voltage drop across line impedances for the grid-forming inverters. An adaptive

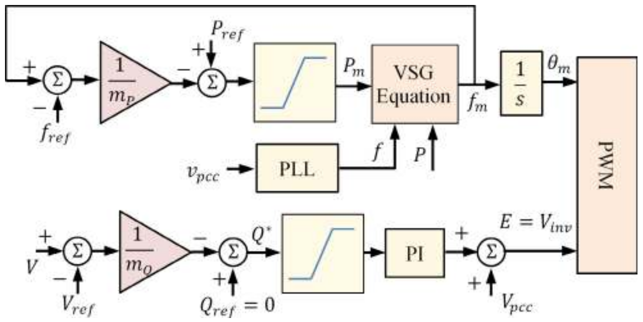


FIGURE 8. A basic block diagram for VSG control technique.

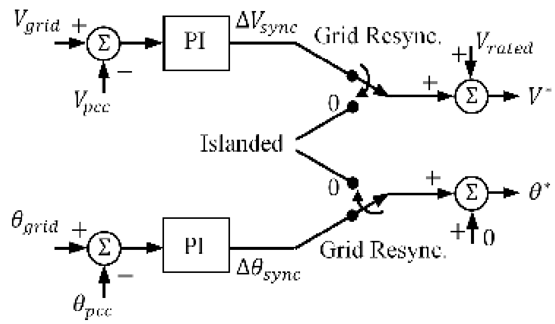


FIGURE 9. Block diagram of grid resynchronization control.

virtual inductance can be helpful in such cases. Therefore, the virtual inductance for droop control should have a static element, which should stay within 0.05-0.15 *pu* to ensure that the equation for power transfer holds [32]. Besides, an adaptive virtual impedance should be incorporated to ensure that reactive power is properly shared among grid-forming inverters [33]. Furthermore, a droop control method should achieve zero error frequency restoration.

b: VIRTUAL SYNCHRONOUS GENERATOR CONTROL TECHNIQUE

The virtual synchronous generator (VSG) control technique for grid-interactive inverters mimics the dynamic behavior of electric machines, see Fig. 8. To fully achieve VSG, a DG should be equipped by dc-bus energy storage to play the role of the kinetic energy reservoir in the rotating mass of an electric machine [34], [35]. The swing equation derived from the equation of motion can be expressed as:

$$P_m - P = J\omega_m \frac{d\omega_m}{dt} + D\left(\frac{\omega_m - \omega}{\omega_{ref}} S_b\right) \tag{7}$$

where, J denotes the virtual inertia, D is the damping factor, ω_m, ω, and ω_{ref} are the virtual rotor angular frequency, the angular frequency of the voltage at PCC, and nominal angular frequency, respectively. Also, P_m, P, and S_b are the virtual shaft power determined by the droop (governor) equation, the active power injected to the grid measured at PCC, and the power rating of the inverter, respectively.

The inertia of inverter-based DGs is inherently zero unless some virtual inertia has been implemented into the control schemes. Therefore, microgrids with a high number of inverter-based DGs can be susceptible to sudden load changes and disturbances. Particularly for grid-forming inverters in droop mode, the under-frequency, and over-frequency relays can be triggered under sudden changes [34]. The virtual synchronous generator method can be implemented for better dynamic performances by adding virtual inertia to the inverter. Similar *Q-V* and *P-f* equations, as given in (6), can be combined with (7) to form a virtual synchronous generator in which the *P-f* droop equation is the governor of the virtual synchronous generator, as shown in Fig. 8. Furthermore, an energy storage element can be added to the dc-bus of the inverter for providing the energy reserve necessary to supply virtual inertia [35].

Centralized schemes for grid-forming inverter such as the master-slave approach might be more suitable for microgrids containing inverters in close proximity such as in smart buildings, where a communication link between the inverters can be quickly established. For microgrids spread over a distribution network, a decentralized approach might be more suitable, whereas the droop control or virtual synchronous generator scheme can be used based on the availability of energy storage units.

III. FLEXIBILITY AND SELF-ADAPTING FEATURE

Forming an islanded microgrid may place inverters in a weak grid condition. Therefore, self-adaptation should be added into the controller of smart inverters for larger stability regions and seamless transitions between modes of operation.

A. SEAMLESS TRANSITION AND ISLANDING DETECTION

Power grids can encounter a loss of utility power because of natural events or physical and cyberattacks. Therefore, inverters should be programmed to detect loss of utility power, and consequently, shape islanded microgrids. The terminal voltage of inverters is measured by their local controllers. Therefore, the simplest way to detect loss of grid is to determine whether the measured voltage and frequency are outside the normal range of operation defined in the IEEE Std. 1547-2018 [16]. The time interval during which the voltage falls outside the normal range must be considered, according to IEEE Std. 1547-2018, before performing any reaction to avoid false detection. The inverter can be separated from the grid using a static transfer switch (STS). When a single inverter is operating in an islanded mode, reconnection to the grid is simple since the voltage buildup at the other end of the STS can be detected, and the inverter can be synchronized to the grid before reconnecting. To avoid high current transients, the difference in voltage amplitude and phase across the STS can be fed to two PI controllers, which would then generate compensation signals to be added to the inverter voltage amplitude and phase for slowly resynchronizing to the grid, as shown in Fig. 9 [30]. However, the STS could be far away from the inverter, and as such, the synchronizing information would not be readily available. In such cases, the microgrid has to be equipped with some sort of supervisory controller, which can provide the synchronizing information through low bandwidth communication signals [30]. Alternatively, there are methods that utilize only the inverter-side current and voltage measurements with no control over the grid-side of STS. These methods typically require a quick detection of the grid phase angle to minimize the transient overcurrent [36], [37].

B. SUPERVISORY CONTROL USING FORECASTING DATA

Besides the economic dispatch, a supervisory or tertiary controller can enable the interconnection of microgrids to form a grid of microgrid through sharing synchronizing data [9]–[13], [38], [39]. Additionally, some issues arising from the intermittent nature of renewable energy sources can be mitigated with a supervisory structure that has access to weather forecasting data. On a particularly windy day, the wind speed limit of the wind turbines might be violated, which will cause the wind turbines to shut down. Similarly, the output of a PV array can suddenly drop following the passing of a large cloud. As the penetration of renewable energy sources is increasing, the loss of a wind farm or solar farm could cause frequency and voltage oscillations. Alternately, if the weather forecast is known beforehand, the solar and wind farms can be gradually powered down while the remaining sources, particularly high inertia synchronous generators, can be slowly powered up to avoid any under-frequency trips.

C. ADAPTIVE STABILIZERS

Weak grids make inverters susceptible to voltage deviations, while a severe weak grid case can make the inverter unstable, which will result in sudden inverter disconnection. The sudden loss of power from an inverter in islanded microgrids could cause a cascaded failure event in a newly formed microgrid after the loss of utility power. The current control loop bandwidth, voltage feedforward path, phase-locked loop (PLL), and filter parameters are the elements that can be appropriately designed for improved dynamic performances [37], [40]–[43].

As discussed earlier, the grid parameters play a significant role in shrinking the normal operating region of inverters in weak grids. Thus, including an adaptive element into the controller of smart inverters is advancing the inverter flexibility [44]–[46]. In [44], an adaptive control scheme to enhance the stability of inverters is presented based on the online estimation of grid impedance. For larger values of grid impedance, the PLL bandwidth is lowered to keep the inverter in the stable region. However, the PLL bandwidth had to be lowered considerably to ensure stability, thus introducing a tradeoff between stability and dynamic performance. In [45], an active damper is added to the system, which essentially introduces an additional resistive term in the inverter circuit that can be varied adaptively to make the inverter more robust against changes in a grid condition. The active damper is realized using an additional low-power single-phase inverter, which ensures stability without adding any complexity to the controller. However, it requires additional circuitry contributing to additional size and cost. In [46], the gain of the voltage feedforward path has been updated adaptively to enhance stability in weak grids. However, the technique presented in [46] required grid impedance estimation, implemented using a band-pass filter. In summary, to make smart inverters robust against weak grids, adaptive elements need to be introduced in the control scheme. While the conventional controllers with fixed parameters are commonly used, adding adaptive feedforward and virtual impedance schemes seem to be the most promising solutions to realize the adapting feature for smart inverters.

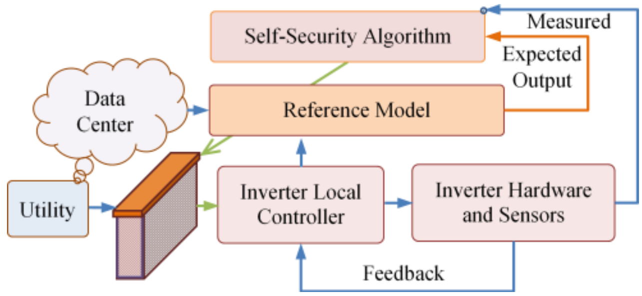


FIGURE 10. A model-reference approach to examine and determine cyberattacks versus healthy supervisory control commands from the utility.

IV. COMMUNICATION AND SELF-SECURITY FEATURE

The performance of smart inverters in both grid-forming and grid-following modes can be improved with access to external data. However, data packet transmissions between smart inverters and the utility operator through a communication network can make inverters subject to cyberattacks and unintentional human mistakes [47], [48]. As revealed in Fig. 10, this challenge can be addressed through implementing a reference system (model) to distinguish a malicious setpoint from a regular setpoint receiving from the power utility. Secure communication can be achieved using known message authentication code (MAC) methods, to confirm if a setpoint came from the utility and has not been altered. Nonetheless, the utility computer can be hacked, and manipulated setpoints can be sent with secure tags. One way to form a self-secure inverter is to identify the normal operating region, see Fig. 2, and used it along with the grid codes as the knowledge-base. If a hacker manipulates the inverter setpoints, the inverter can first examine the new setpoints using the reference model, and then, may refuse to engage them if the projected output falls outside of the safe operating region of the inverter. Based on various types of cyberattacks [49], [50], different and more sophisticated methods can be developed.

A communication network for grid-interactive inverters must be secure and scalable while providing low latency, high range, and adequate data rate [10]. The IEC 61850 standard provides a platform for advanced interoperability of intelligent electronic devices (IEDs), e.g. smart inverters, from different vendors [12], [13]. In IEC 61850, the data model can be mapped to multiple protocols, e.g. GOOSE, MMS,

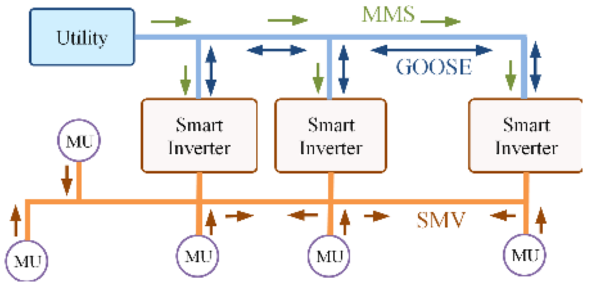


FIGURE 11. A basic implementation for a communication network needed between the utility operator, smart inverters, and measurement units.

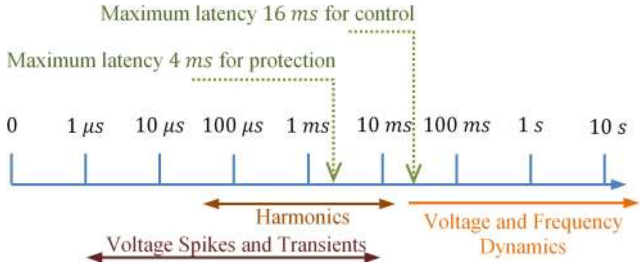


FIGURE 12. Timeline of transient and dynamic phenomena in power grids and maximum latency requirements for transmitting protection and control data packets based on the IEC 61850 protocol.

and SMV. The generic-object-oriented-substation-events (GOOSE) protocol is for exchanging information between IEDs in a publisher/subscriber arrangement, whereas the manufacturing- message-specification (MMS) protocol is for transferring real-time data and supervisory control data between IEDs and the utility operator in a client/server format, and the sample-measured-values (SMV) protocol is for transmitting digitized signals from measurement units, e.g. sensors, to IEDs, see Fig. 11. Notice, the processing and end-to-end data packet transmissions have inherent delays, which will confine the effectiveness of a centralized control scheme on suppressing transient and fast dynamic phenomena [10], [12], [13], [51]–[53], see Fig. 12. One may observe that a cyberattack can be planned by altering the end-to-end packet delays between smart inverters, sensors, and the utility for a specific event, making the overall system unstable.

A communication network can be wired, e.g. optical fiber, power line communication (PLC), etc., wireless, e.g. cellular, Wi-Fi, etc., or a combination of both [10], [12], [13]. The wired communication methods are typically more immune to electromagnetic interferences (EMI), but they are less scalable in comparison with the wireless techniques. Using power lines for data communication is the technology that has a long history in relay and protection systems and provides a low-cost solution, but it has the lowest data rate compared to other wired communication technologies. Also, inverters may lose their access to the external data in islanded mode using power lines for data communication. A wireless communication network with mesh topology is more fault tolerance, but due to the routing process, the actual data rate may significantly be reduced to an unacceptable level. To avoid complicated methods and provide high scalability, sparse communication technique has been proposed as a solution in which inverters need to communicate only with their nearby smart devices and inverters [27], [28].

V. FAULT DIAGNOSIS AND SELF-HEALING FEATURE

Incipient fault diagnosis and self-healing of inverters is a crucial feature. It becomes even more critical for inverters operating in islanded microgrids and grids with high penetration of inverter-based DGs. In islanded microgrids, the total load of the system is shared among the inverters. As a result, if an inverter gets suddenly disconnected due to a fault, it could trigger a cascaded event similar to the weak grid case that may collapse the entire system.

Unlike the other features considered for smart inverters, real-time fault diagnosis, and fault-tolerance techniques for inverters in different applications such as in motor drives, and electric powertrains can be applied for grid-tied inverters [54], as long as their implementation is not application-specific.

Fault-tolerant inverters can be broadly categorized as non-redundant and redundant techniques [55]. Following the detection of an incipient fault, inverters using non-redundant techniques have to switch to a different control scheme to continue operation with a fewer number of active devices. The main components, e.g., semiconductor devices and dc-bus capacitors, also have to be overrated for non-redundant techniques. Even if an inverter remains operational after isolating an internal fault, the resulting grid currents can be severely asymmetric with non-redundant techniques.

Redundant techniques for two-level inverters require an additional leg with two semiconductor devices. For two-level inverters equipped with an auxiliary leg, the faulty leg needs to be isolated, and the auxiliary leg has to connect to the circuit appropriately. In redundant fault-tolerant inverters, each switch is equipped with a fast-response overcurrent fuse to isolate the device in case of a short-circuit fault. Once the device is isolated, that branch of the circuit will act similarly to the case of an open-circuit fault. Furthermore, an appropriate open-circuit fault detection technique should detect the location of a fault. Depending on the location of a fault, the proper connecting switch should be closed to introduce a device from the auxiliary leg into the circuit. Low-speed semiconductor switches are typically used as the connecting switches, as the connecting switches commutate at the fundamental frequency.

Although two-level inverters are commonly used for grid-tied applications, modular multilevel inverters are inherently more tolerable of internal faults than two-level inverters [54], [56]–[62]. However, they are normally used for high and medium voltage applications. If the self-healing feature is desired, multilevel inverters should be recommended. One of the best topologies for realizing a fault-tolerant inverter is the cascaded h-bridge (CHB) inverter, where the inverter neutral point is not grounded. A discrete method, called fundamental phase-shift compensation [59], [60], is demonstrated in

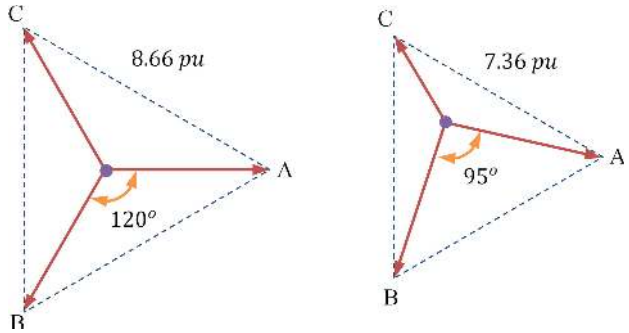


FIGURE 13. Phasor diagrams in the prefault and a postfault scenario after isolating two cells of Phase-C of an 11-level CHB inverter when the phase-shift compensation technique has been implemented.

TABLE 2. Corrective angles after bypassing one and two faulty cells in a 11-level CHB inverter.

A	B	C	θ_{AB}	θ_{BC}	θ_{CA}	V_{LL} (p.u.)	ΔV_{LL} (%)
5	5	5	120^o	120^o	120^o	8.66	0
5	5	4	107^o	126.5^o	126.5^o	8.04	−7.2%
5	5	3	95^o	132.5^o	132.5^o	7.36	−15%

Fig. 13, in which the voltage magnitude is degraded, but the three-phase system remains symmetrical after bypassing faulty cells, with a floating neutral point. In Table 2, two fault scenarios and their corresponding corrective angles are given in Table 2. Notice, the CHB inverter in this table is an 11-level inverter, in which the line-line prefault voltage magnitude is equal to 5 $\sqrt{3}$ p.u., assuming the voltage of each cell is 1 p.u. In [61], a continuous self-healing technique has been presented. This technique enables CHB inverters to provide a symmetrical ac voltage from a set of asymmetrical time-variant input dc source voltages using an adaptive PWM technique. Two alternative methods for implementing adaptive SPWM have been proposed in [61]. The first method, called the sensor-per-source (SPS) algorithm, requires all cell input voltages to be monitored in real-time while the second method, called the sensor-per-leg (SPL) algorithm, only requires real-time monitoring of the leg's line-to-neutral output voltage. More comprehensive self-healing techniques and corrective actions can be implemented for modular battery-powered grid-forming inverters to enhance the availability of smart inverters.

VI. CONCLUSION

The desired features of smart inverters have been categorized as self-governing, self-adapting, self-security, and self-healing in this paper. The self-governing role of inverters has been defined as providing voltage support and ancillary services for the power grid, ensuring the grid codes and standards. Also, constraints of providing ancillary services under unbalanced anomalies have been determined. Furthermore, the advantages and disadvantages of both centralized and decentralized control schemes for grid-forming operations have been studied for islanded mode. The loss of utility power detection and seamless resynchronization to the grid has been referred to as the grid-adapting feature. Moreover, adaptive and virtual elements have been recognized as valuable features for inverters in weak grids. The importance of engaging communication networks to control grid-tied inverters has been discussed. The need for device-level security against cyberattacks has been identified and referred to as the self-security feature. Furthermore, the communication requirements and the latency problem have been briefly discussed. Lastly, the ability to detect internal faults and perform necessary corrective actions have been identified as a desired feature for smart inverters, preventing the inverter from a sudden shutdown. These features intensify the role of a grid-tied inverter from being just a reactionary to a proactive device, and all are the hallmarks of the next-generation smart inverters.

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