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Review of Power System Support Functions for Inverter-Based Distributed Energy Resources-Standards, Control Algorithms, and Trends

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ABSTRACT Penetration of renewable energy in power systems has been increasing in the past decades in response to increased global electricity demand and concerns for the environment. Distributed energy resources (DERs) based on renewables have experienced rapid growth thanks to the incentive programs and broad-based participation. With the growing prevalence of DERs, the risk of grid instability and vulnerability increases due to the intermittent nature of renewable energy. At the same time, the voltage and frequency deviation problems emerge more often when the reverse power flow occurs under supply-demand imbalance in distributed power systems. Standards and grid codes have been issued for DER inverters to interconnect with the distribution grid. The updated standard and grid codes expect DERs to provide a variety of power system support functions in order to incorporate higher DER penetration and to maximize DER value to the grid. This paper provides an overview of the power system support functions from renewable DER inverters, which are categorized as: voltage regulation by active/reactive power control, frequency regulation by active power control, voltage ride-through, and frequency ride-through. The benefits and drawbacks of each algorithm are presented and compared with its predecessor, manifesting the logic in the evolution of the algorithms.

INDEX TERMS Distributed energy resources (DERs), inverters, power system support functions, reactive power control, voltage ride-through.

I. BACKGROUND

For past century or so, electric power systems are mainly bulk power systems (BPSs) consisted of generation, transmission, and distribution networks. One of the most significant changes to power systems around the world has been the rapid expansion of distributed energy resources (DERs) and the transition from larger conventional synchronous machine resources to smaller-sized resources with varying generation characteristics. From the perspectives of International Renewable Energy Agency (IRENA) and Independent Electricity System Operator (IESO), DERs are defined as "small and medium-sized power sources or controllable loads connected to the local distribution network or a host facility within the local distribution system that can potentially provide services to the power system" [1], [2]. DERs can include distributed generation (DG) units such as behind-the-meter generators, combined heat and power plants; electricity storage facilities including batteries and electric vehicles; and directly or indirectly controlled loads such as in a demand response program. These resources are typically smaller in scale than the traditional generation facilities that serve most of demand. In this paper, DERs mainly refer to renewable power sources and energy storage systems (ESS), where the renewable power sources are referred to as renewable DERs. Demand side management resources like controllable loads that do not produce electricity are beyond the scope of this paper.

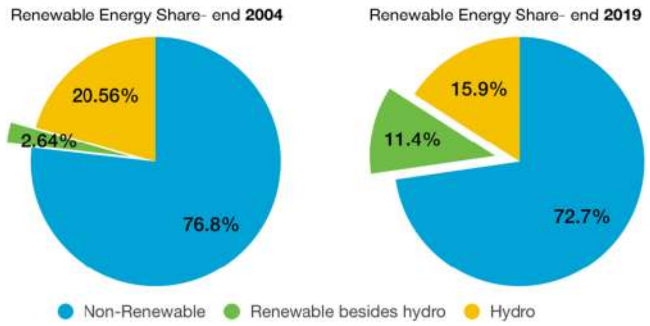

FIGURE 1. Renewable energy share of global electricity production in 2004 vs 2019 [5], [6].

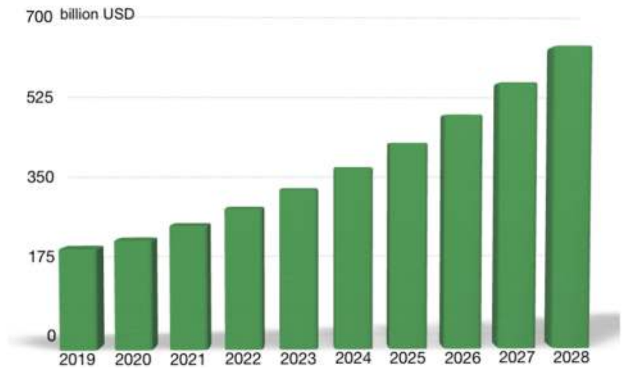

FIGURE 2. Projected global DER market growth [8], [9].

This paper is intended to provide an extensive review on the power system support functions of DERs. The review narrates the development and evolution of the control algorithms in power system support functions such as voltage regulation, frequency regulation, voltage ride-through, and frequency ride-through. The background and market status of DERs are summarized in Section I. The values and challenges of DERs to the grid are described in Section II. The updates of interconnection standards and grid codes are presented in Section III. The review of current work on power system support functions by DERs is discussed in Section IV. The trends of DER development are predicted in Section V.

While defining DER is an important first step, it is essential to recognize how these resources have developed, grown, and exerted their impact on the power system. In recent years, the whole world is experiencing a growing interest in a more diverse electric grid with increasing penetrations of renewable resources such as wind and solar power systems, in reaction to a growing concern on climate change and energy crisis. As shown in Fig. 1, the renewable energy share in global electricity production has increased from 2.64% at the end of 2004 to 11.4% at the end of 2019 in the face of persistent investment in fossil fuel power capacity and subsidies [3], [4].

The proportion of DERs in wind power systems remains small [5], while that in PV systems grows steadily in past decades. Enormous usage of rooftop PV panels for residential, commercial and industrial applications is one of the essential contributions to the growing proportion of DERs. The U.S. Energy Information Administration (EIA) estimates that the solar electricity generation increased from about 5 million kWh in 1984 to about 107 billion kWh in 2019, of which 33% was from small-scale or distributed PV systems [6]. According to IRENA, the installed capacity of DERs until 2019 reached 31.6 GW in China, 20.125 GW in U.S, and 7.198 GW in Australia [1].

DERs have been integrated into wholesale electricity markets and are treated on a par with other wholesale market resources [7]. Current development in regulatory policies, rising environmental concerns, frequent outages coupled with increasing electricity costs have resulted in the progress of the overall market. Grand View Research Report [8] and Navigant Research report [9] provided a quantitative analysis of the global market for DER technologies, which covered DG, electricity storage facility, electric vehicles, and demand response. Fig. 2 shows the average market growth from 2019 to 2028 projected by Navigant Research and Grand View Research. The global DER capacity in 2020 is around 184 GW worldwide, and is expected to reach 436 GW in 2027 worldwide [8].

II. BENEFITS AND CHALLENGES OF DER GRID INTEGRATION

A. DER BENEFITS AND VALUES

The emerging of DERs was attributed largely to energy (both oil and electricity) crisis and power industry deregulation while alternative and renewable energy resources were pursued to alleviate global environmental concerns such as greenhouse gas emissions from traditional fossil-fuel based generation. Additional consumer benefits and values to grids have been identified and summarized below, especially for power electronics-based DERs.

1) *Local power reliability.* Many DERs are small-scale behind-the-meter generators within or in close proximity to consumer sites. They may offer backup or emergency power during grid outage due to extreme weather or other utility faults, thereby enhancing local power reliability.
2) *Power quality.* Power electronics-based DERs can be designed to compensate for grid voltage variations, unbalance, and harmonics. These could happen at a longer feeder end in rural areas or in areas with large nonlinear industry loads, where power converters are deployed to support grid voltage profiles, manage grid voltage sags and swells, and perform as active filters.
3) *Energy efficiency and asset utilization.* Power electronics-based resources can play important roles on decentralized voltage/var optimization (VVO) and conservation voltage reduction (CVR), which helps the utility save energy and improve energy efficiency. As smart devices, power converters can be utilized to control grid power flow dynamically to maximize various grid assets' utilization.
4) *Energy storage capability.* Energy storage systems are special DERs with four-quadrant operation capability. They can not only provide mobility and emergency

power, but also help grid manage load profiles (peak-shaving and valley-filling), smooth renewable power, and provide fast ramping up and down power for ancillary services avoiding expensive spinning generators.

5) *New functionality, fast dynamics and enhanced controllability.* Power electronic systems can provide additional grid controllability in a fast-responding way comparing to rotational machines. For protection applications, this fast response is beneficial to reduce the fault current magnitude and isolate the fault quickly. With advanced control algorithms in smart inverters [10], [11], power grids can be equipped with fast controlled resources in a decentralized manner.
6) *Grid resilience.* Resilience is defined as the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions such as deliberate attacks, accidents, or naturally occurring threats or incidents. For power grids, various grid-hardening approaches, distribution automations, and self-healing techniques have been utilized to improve grid resilience. Both DERs and microgrids play important roles during grid recovery or restoration following post-event, where power electronics-based DERs serve as fundamental resilience tools [11].

Currently, DERs are mostly installed at the distribution networks, but they are becoming major players in future deployment of grid planning and operation, with technology advances (e.g., smart inverters), continuingly reduced cost (e.g., energy storage cost), sustainability and resilience requirements, and new standards and regulations, which will be reviewed in the following section in this paper.

B. DER GRID INTEGRATION CHALLENGES

There exist grid integration challenges for DERs, albeit all the benefits and values, with conventional power grids designed for centralized generation and controls. Therefore, grid impacts of DERs have been studied extensively in the literatures. Nonetheless, few studies focus on grid impacts under a scenario of high penetration level of DERs.

1) *Lack of interoperability standards*. Interoperability is defined to be the ability of two or more systems or components to exchange information and to use the information that has been exchanged, according to ISO/IEC/IEEE 24765 standard. The interoperability has been identified as an important R&D area to enable interactive power grid and is needed for DERs to offer plug-and-play capabilities and to cooperate among grid devices of heterogeneous types or from different vendors. DERs come in different types and from different vendors with different communication protocols. Although DER interconnection standards have been developed in recent years, such as IEEE Std. 1547-2018, a common standard on interoperability among DERs and system operators is still evolving. California Rule 21 has recommended IEEE Std. 2030.5 (SEP2) for utility communications of smart inverters. USA DOE national laboratories are developing service-oriented energy interfaces to address the interoperability issues.
2) *Lack of detailed DER modeling*. Conventionally for BPS analysis and simulation, DERs are mostly modeled as aggregated net constant power loads at distribution substation nodes. With increasing penetration of grid-following DERs and their inherent different fault-handling behaviors, the utility has been experiencing the impacting issues, such as the 50.2 Hz problem in Europe and the Duck Curve phenomena in Hawaii and California, U.S. Furthermore, with more and more DERs adopting grid-supporting or grid-forming control technologies, grid dynamics are gradually changing and simple negative load representation of DERs will not reflect the grid-DER interaction. Therefore, it becomes necessary to model detailed DER dynamics and transient behaviors for BPS planning and operation.
3) *Increased control points and operation burden*. Comparing to large MW or GW-scale power plants, DERs are typically small-scale distributed generations. If a large synchronous generator is displaced by tens or hundreds of dispersed DERs, the number of control points and control devices will inevitably increase and significantly add to system operator's burden at secondary control level, e.g., autonomic generation control (AGC), given that these DERs may be stochastic and non-uniform by nature. In certain cases, the situation may become unrealistic for real-time control due to system communication and control bandwidth. Autonomous operation and decentralized control will help alleviate this possible control challenge.
4) *New protection scheme and configuration***.** Existing power system protection systems are designed mainly for machine-based generators and in distribution systems for unidirectional power flow. With DERs installed in the distribution feeder, bi-directional power flow could occur. Furthermore, the short-circuit current contribution of inverter based DERs are typically lower than the contribution of synchronous generators, which requires new protective relay sensors to detect lower current values and advanced protection coordination schemes.
5) *New stability phenomena*. Traditional power grids are rich of large rotating machines and therefore small-signal instability or oscillations mainly happen at sub-synchronous frequencies, e.g., 0.1 to 1.0 Hz for inter-area mode oscillations, 1.0 to 2.0 Hz for local plant mode oscillations, 2.0 to 3.0 Hz for intra-plant mode oscillations, and 10 to 46 Hz for torsional mode oscillations. For a power system with a large number of power electronics devices, the instability could happen at supersynchronous harmonic frequencies, e.g., a couple of hundreds up to a few kilo Hz. The root causes of these new instability phenomena are still not well understood, but the harmonics and control designs of individual power electronics converters seems to be attributed

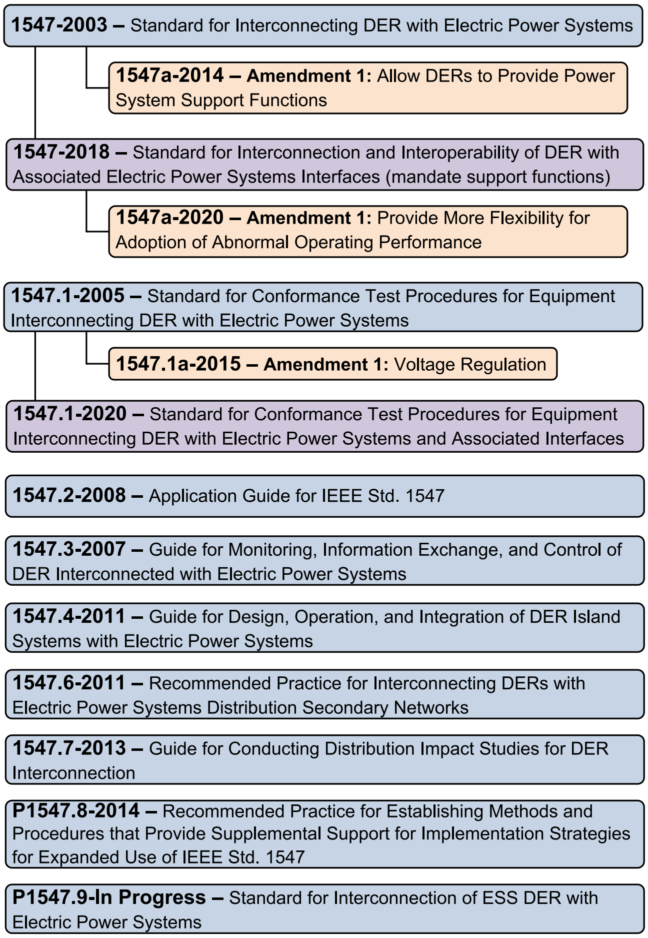

FIGURE 3. Evolution of IEEE Std. 1547 series.

to the potential issues and conventional power system analysis tools do not predict these issues precisely. Therefore, there exist control challenges on power system stabilization with a large number of inverter-based resources.

III. STANDARDS AND GRID CODES

The traditional perspective of electricity infrastructures is large central power plants providing MW or even GW level of power. The power flow tends to be one-way through high-voltage transmission lines over long distance to distribution networks that then deliver power to a multitude of clients. With the emergence and advancement of distributed generation and renewable energy technologies, U.S. public utility commission (PUC) legislates technical standard for implementing DER interconnections since the consumer-sited generation led to two-way power flows and intermittency from renewables, at sites dispersed throughout the system [12]. The IEEE Standard (Std.) 1547 has been a foundational document for the interconnection of DER with the electric power system, and the evolution of 1547 series is shown in Fig. 3. As the first IEEE 1547 series of standards for DER interconnection, IEEE Std. 1547-2003 mainly specifies the minimum functional technical requirements such as the power quality, voltage levels and frequency ranges as well as safety and protection that are universally needed to help ensure a technically sound interconnection [13]. IEEE Std. 1547.1-2005 specifies the type, production, and commissioning tests that shall be performed to demonstrate the interconnection functions and equipment of the DERs conform to IEEE Std. 1547. IEEE Std. 1547.2-2008 provides technical background and application details, characterizes various forms of DER technologies, and provides background and rationale of the technical requirements of IEEE Std. 1547. IEEE Std. 1547.3-2007 intends to facilitate the interoperability of DER and help implement monitoring, information exchange, and control to support the technical and business operations of DERs. IEEE Std. 1547.4-2011 includes the ability to disconnect from and reconnect to part of the area electric power system while providing power to the islanded microgrid; IEEE Std. 1547.6-2011 gives an overview of distribution secondary network system design, describes considerations for interconnecting DER with networks, and provides potential solutions for the interconnection of DERs in network distribution systems. As the renewable DER penetration is increasing and starting to impact the power system operation and dynamics, IEEE Std. 1547.7-2013 provides alternative approaches and good practices for engineering studies of the potential impacts of DERs interconnected to the electric power distribution system [14]. P1547.8-2014 was about recommendations addressing DER interconnection system-level potential adverse effects, but the project was withdrawn in 2016; P1547.9 is in progress of taking the interconnection of ESS into consideration. The interconnection rules at that time accommodate the small amounts of the power flows from DER systems, but not adequately cope with the expected large amounts of DERs to support the paradigm shift in distribution systems.

Under higher penetration of renewable DERs, DER self-protection is not suitable any more in grid faults, since disconnection of a unit may lead to widespread disruption and cascading failures. Therefore, in order to increase the hosting capacity of renewable DERs, IEEE standards and grid codes throughout the world have been changing and updated to require DERs to provide power system support functions and remain connected for a certain period of time when a grid fault happens. IEEE Std. 1547a-2014 first established an amendment for IEEE Std. 1547-2003, which allows DERs to provide power system support functions such as voltage regulation, voltage ride-through and frequency ride-through with changes in real and reactive power output to support the grid [15]. The amendment IEEE Std. 1547.1a-2015 was then prepared in response to IEEE Std. 1547a-2014 for the addition of voltage regulation. Periodic tests as well as DER design and installation evaluations are specified in IEEE Std. 1547.1-2020 for the conformance to IEEE Std. 1547 [16]. IEEE Std. 2030.2 was affirmed in August 2014 to provide guidance for power system support functions by energy storage systems (ESS). California PUC updated CA Rule 21 in 2015 to make autonomous power system support functions as a requirement

TABLE 1. Evolution of DER Interconnection Standards

	1990's	2000's	2010's~2020
EVOLUTION OF STANDARDS	IEEE 519-1992 ANSI C84.1-1995 UL 1741-1999	IEEE 929-2000 IEEE 1547-2003 UL 1741-2010 CSA C22.2 No.107.1-01	IEEE 1547a-2014 & 2018 & 2020 IEEE 2030.2 UL 1741 SA & CA Rule 21 & HI Rule 14H (U.S.) CSA C22.2 No.107.1-16 & CSA C22.3 No.9 (Canada) EN 50438:2013 & EN 50549:2019 (Europe) CEI 0-21 (Italy) VDE-AR-N 4105: 2011-08 & 2018-11 (Germany) EREC G98 & G99 (Great Britain)
DER INTERCONNECTION REQUIREMENTS	Compliance with specifications: *Voltage range* *Frequency range* *Synchronization* *THD (harmonics)*	+ Safety & protection: *Anti-islanding* *Narrow PF* *Dis- and re-connection* Power quality: *THD & TDD* *Flicker* *DC injection*	+ Power system support functions: *Voltage & frequency regulation* *Voltage & frequency ride-through* *Power curtailment* *Ramp rate* *Wider PF adjustment* *Grid forming* *Black Start*

for DERs, and Hawaii PUC defined eleven grid supportive functions in HI Rule 14H. In response to the new grid supportive requirements, Underwriters Laboratories (UL) published UL 1741 Supplement SA in 2016 as the test criteria to certify the new DER functions. IEEE Std. 1547-2018 mandates the power system support functions in IEEE Std. 1547a-2014 and includes frequency-droop regulation and inertial response to the rate of change of frequency (ROCOF) in order to address the interoperability and associated interfaces between DER and the grid [17]; the interoperability and associated interfaces are built from IEEE Std. 2030, which mainly refer to the capability of two or more systems externally exchanging and readily using information securely and effectively. The amendment IEEE Std. 1547a-2020 revises the ranges of trip clearing time settings for DER in undervoltage operating scenario to allow wider ranges that can broaden the adoption of the standard [18]. Canadian interconnection standard CSA C22.3 No. 9 published in 2020 includes requirements for power system support functions similar to those in IEEE Std. 1547-2018, as well as a description of test procedures referred to UL 1741 SA [19]. Various Canadian provincial utilities, such as AESO, IESO and Hydro Quebec (HQ) specify different parameters depending on the network characteristics [20].

Numerous international standards have also been published to require DERs to provide power system support functions. For example, the European grid code EN 50438:2013 requires DERs below 13.8 kVA to provide a PF between 0.95_{lead} and 0.95_{lag}, and DERs above 13.8 kVA to provide a PF between 0.90_{lead} and 0.90_{lag}, as visualized by the triangular-shaded are in Fig. 4 [21]; the updated EN 50549:2019 adds voltage ride-through, frequency ride-through, and ranges of ROCOF [22]. Likewise, the Italian grid code CEI 0-21 states similar operating conditions for DERs interconnection with grid [23]. The German grid code VDE-AR-N 4105: 2011-08 dictates that all DERs connected to the grid should apply a PF adjustment to regulate the grid voltage accordingly [24]; the updated VDE-AR-N 4105: 2018-11 includes voltage ride-through, frequency ride-through and power system support functions for ESS [25]. The Great Britain grid code EREC G99 issued in July 2018 incorporates PF adjustment between 0.92_{lead} and

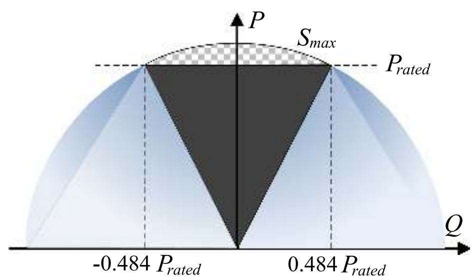

FIGURE 4. DER reactive power requirements.

0.92_{lag} and frequency ride-through to provide system support in the event of a network fault [26]. The reactive power requirements in Fig. 4 vary from region to region, and different grid codes have different clearing time settings for voltage ride-through and frequency ride-through requirements, as will be detailed in the following section. The evolution of the DER interconnection standards from 1990s to present-day is summarized in Table 1.

IV. POWER SYSTEM SUPPORT FUNCTIONS–VOLTAGE AND FREQUENCY REGULATION

Under high penetration level of DERs, the risk of grid instability increases due to the intermittent and stochastic nature of renewable energy, the voltage and frequency deviation problems emerge more often. The classical approaches for addressing this issue are to add more flexible resources such as large generators, VAR control equipment and energy storage system, and to upgrade and reinforce the distribution networks by using larger cables to reduce the impedance. But they give way to more flexible and inexpensive control schemes of DER inverters [12]. At the same time, modern grid codes were updated to include more renewable-related rules for DER inverters to provide power system support functions such as voltage and frequency regulations, power factor regulations, power curtailment and harmonic compensation [18].

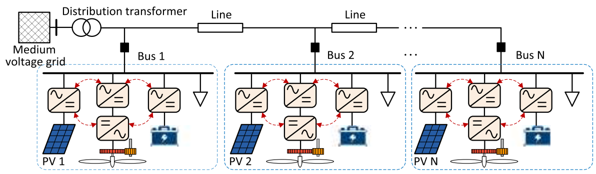

FIGURE 5. Unidirectional single branch radial distribution network.

A. VOLTAGE REGULATION STRATEGIES

1) VOLTAGE REGULATION REQUIREMENTS

Voltage profile of distribution feeders is a key factor of the power quality delivered to the customers. Specifically, in a unidirectional single branch radial distribution network as shown in Fig. 5, a reverse power flow occurs when the production of a feeder surpasses its consumption, which leads to voltage swell and overvoltage problems [27], [28]. The classical approach for addressing this issue is using shunt capacitor banks, tap changing transformers, and online tap changers. Nowadays, IEEE Std 1547-2018 specifies the attributes of voltage and reactive power control requirements that DERs shall provide minimum reactive power injection and absorption capability up to 44% of nameplate apparent power rating [15]. To meet the requirements in the updated grid codes, researchers are focusing on developing and designing flexible and inexpensive control strategies for the DER inverters interfacing renewables with electric power systems. The voltage regulation capability can generally be achieved by four modes of reactive power control functions: the constant power factor (PF) mode, the PF-active power (PF-watt) mode, the voltage-reactive power (volt-var) mode, and the voltage-active power (volt-watt) mode. For the following discussions about the inverter algorithms to achieve the voltage/power control requirements, the wind speed and insolation levels for all DERs are assumed to be the same, and the active power losses due to discrepancies between the inverters with different PF set values are ignored.

2) VOLTAGE REGULATION BY REACTIVE POWER CONTROL

In constant PF method, DER inverters shall operate at a target PF specified by the power system operator regardless of DER location or feed-in active power levels [29], as shown in Fig. 6(a). According to the minimum reactive power requirement for supplemental DER system [15], PF values within $\pm$ 0.9 range shall be achieved by the DER inverters. As the voltage sensitivity to reactive power increases with the distance away from the transformer, constant PF method with location variance is presented in Fig. 6(b) [30], where the inverters close to the transformer absorbs less reactive power and the inverters connected farther away absorbs more reactive power. In this way, the same voltage regulation effect can be achieved with less reactive power absorption in total, which leads to lower current stress and power losses.

To prevent reactive power flow through inverters when the possibility of overvoltage problem is slight, i.e., when the active power production is low, the $\cos\varphi(P)$ method controls the PF as a function of the active power output following a target piecewise linear PF-watt characteristic as shown in Fig. 6(c) [31]. Fig. 6(d) shows $\cos\varphi(P)$ method with location variance that enables the inverters near critical bus to operate with a lower curve (purple line) and the inverters near the transformer to operate with a higher curve (blue line), thus more effectively utilizing the reactive power.

Since high active power generation does not always cause overvoltage problems, $Q(V)$ method as shown in Fig. 7 starts absorbing the reactive power only when there is a voltage increase at the corresponding point of connection (PoC) [32]. In a single branch radial distribution network, the voltage level increases with the distance away from the transformer, and in $Q(V)$ method, the DER inverters absorb more reactive power when the voltage level increases. Therefore, under volt-var mode, DER inverters farther away from the transformer naturally absorb more reactive power than the inverters close to the transformer, which is in accord with the voltage sensitivity analysis. An optimized $Q(V)$ method is presented in [33], which uses advanced communication protocols on a centralized controller to calculate the optimal Q reference for each inverter, but the requirement of a centralized controller and communication systems increases the cost [34] and imposes a heavy computational burden on the controllers [35].

To combine the advantages of $\cos\varphi(P)$ and $Q(V)$ methods, a $\cos\varphi(P, V)$ method is presented in Fig. 8(a) [36]. This method first produces a PF limit for each PV inverter according to the droop function of $Q(V)$, then assigns a target PF on each inverter according to $\cos\varphi(P)$. Fig. 8(b) incorporates the location variance into $\cos\varphi(P, V)$ to further reduce the total amount of reactive power. Similarly, a central reactive power management system (CRPMS) is incorporated into the $\cos\varphi(P, V)$ method [37], which pushes the high-sensitivity inverters to PF limits during high penetration of PV while maintaining the other inverters at their original $\cos\varphi(P, V)$ states. As shown in Fig. 8(c), when the critical bus inverter is saturated with reactive power during high DER penetration, the penultimate inverter is first considered by CRPMS to operate at its PF limit. In addition, there are multi-objective optimization approaches for finding an optimal reactive power set point value to balance the trade-off between current increase and voltage increase [38]–[41].

3) VOLTAGE REGULATION BY ACTIVE POWER CONTROL

The available reactive power capacity of DER inverters is restricted by power rating and current carrying capacity of semiconductor devices. In the case that the reactive power control is not enough for the voltage regulation, DERs shall provide the volt-watt control by curtailing the active power as a function of the voltage at PoC, as shown in Fig. 9. According to Fig. 9(a), the active power curtailment increases with the distance away from the transformer [42]. Thus the revenues for downstream customers are lower than those for upstream customers, which causes inequality among the customers for benefiting from available renewable generation. To spread the

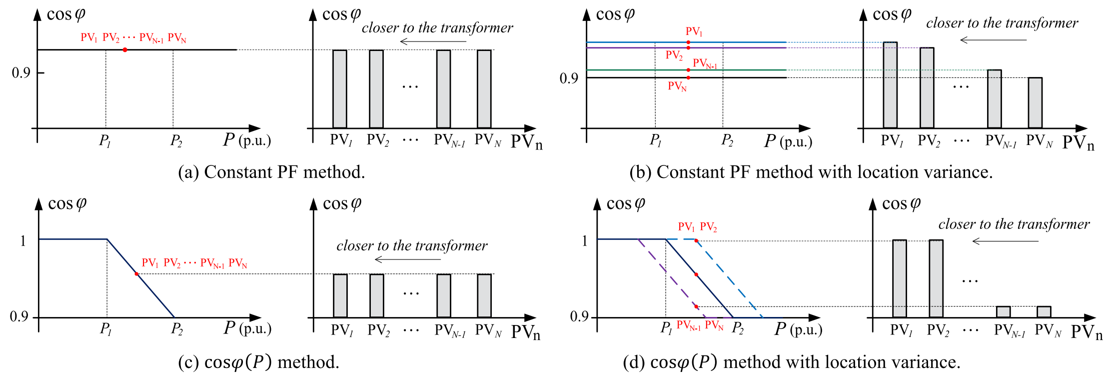

FIGURE 6. Constant PF methods and cosφ(P) methods.

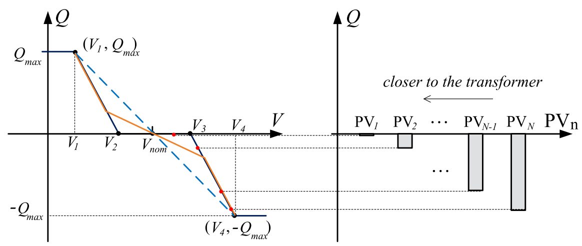

FIGURE. 7. Q(V) method.

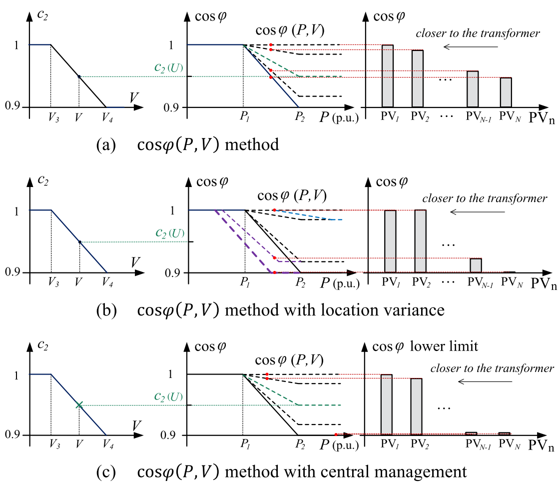

FIGURE 8. cosφ(P, V) methods.

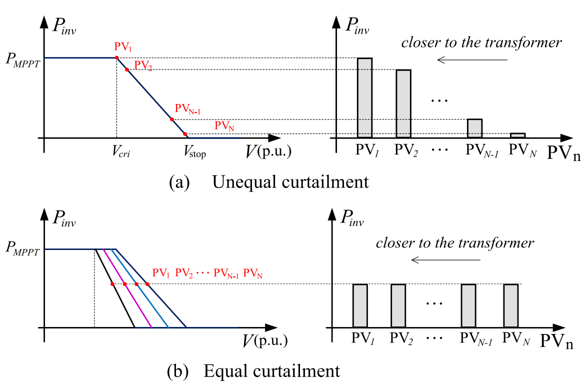

FIGURE 9. Voltage-active power (volt-watt) control mode.

active power losses equally among all customers, the droop coefficient for each inverter is adjusted for fair active power curtailment, as shown in Fig. 9(b) [42], [43]. However, in these active power control (APC) methods, the droop coefficient is calculated for the worst-case scenario to ensure proper range rather than to prevent the voltage from exceeding the unacceptable limit, thus resulting in under-utilization of the available PV energy. To address this issue, some APC methods adjust the droop coefficient in an adaptive way by employing PV generation forecast or adaptive dynamic programming to reduce the energy loss [44]–[46]. Another method performs APC and restores active power generation by using the communication between the inverter controllers in the network [47]. With the consideration that active power curtailment penalizes PV efficiency and system owners, energy storage equipment is added to store the curtailed energy for later use. But the equipment is usually expensive, making it difficult to justify from the cost-benefit point of view [48]–[50].

B. FREQUENCY REGULATION STRATEGIES

1) FREQUENCY REGULATION REQUIREMENTS

The majority of electrical power in the world is generated by fossil-fuel power plants using synchronous generators that are rotating in lockstep. Grid frequency is a critical factor of the power system for the coordination of the paralleled synchronous generators. Regardless of the original power sources, all generators tend to behave in a similar manner–the system frequency decreases as the power drawn from them increases, and larger power imbalance will lead to larger frequency deviations. Conventional generators that are not limited by fuel availability (fossil, hydro) usually have stable and stiff frequency characteristics due to the rotational inertia of synchronous generators. With the increase of power electronics-based renewable generation, the frequency characteristic becomes softer due to the reduced system inertia. The random variations in sources and loads will lead to large frequency deviations and ROCOF. As a result, DERs are required to provide frequency support functions according to the updated grid codes, supplementing or replacing some amount of the conventional inertial response [51]. The frequency regulation are provided through power electronic converters [52],

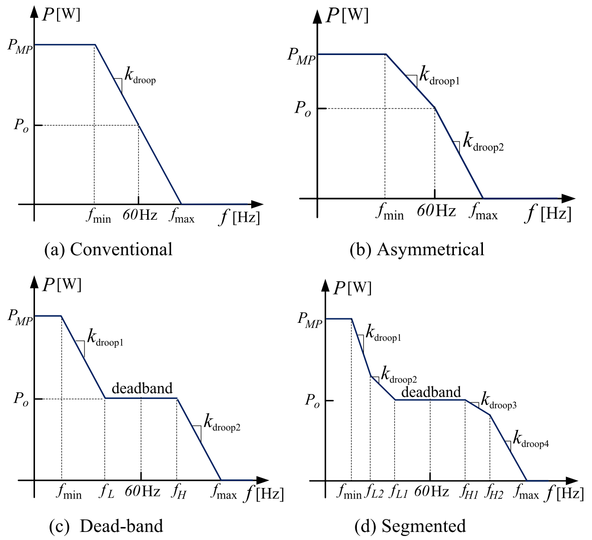

FIGURE 10. **Frequency droop control methods.**

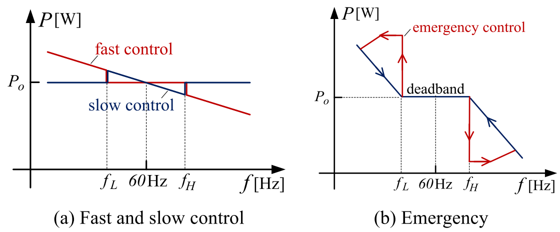

FIGURE 11. **Frequency droop control with fast and slow control.**

which can respond very fast in a manner similar to the inertial response from a conventional generator.

To include frequency regulation capability, DERs usually have pre-curtailment for active power reserve or headroom in case of frequency contingency. Various power curtailment methods have been discussed in the literature [52]–[57], shifting the operating point toward the left or right side of the MPPT curves so that the DERs are operated at a lower power P_o instead of the maximum power P_{MP}.

2) FREQUENCY REGULATION BY ACTIVE POWER CONTROL

Conventional frequency-droop operation adjusts the active power output as a function of system frequency following a frequency-power piecewise linear characteristic as shown in Fig. 10(a) [58]–[60]. The basic principle of the droop control is to increase the active power reference when the grid frequency is below the nominal value and to decrease the active power reference when the grid frequency is above the nominal value [63]. The active power reference is adjusted according to the frequency deviation, predefined droop coefficient, power limit and frequency limit [62]. All upward reserve services from renewable DERs require pre-curtailment, which will incur an opportunity cost of reduced energy sales. Concerning with this problem, the coefficients of the droop control in over-frequency and under-frequency domains can be set independently and differently, as shown in Fig. 10(b), to increase the operating power point. Since a slight deviation due to the measurement tolerance or sensor noise can frequently trigger the regulation around the nominal frequency, a dead-band is inserted into the power-frequency piecewise linear characteristic, as illustrated in Fig. 10(c), to prevent the jitters in response to small frequency deviations [63], [64]. The power-frequency piecewise linear characteristic with dead-band can also be represented by a pointwise method, where the droop curve is constructed by connecting the dots [65]. Since the frequency droop control methods in Fig. 10(a)∼(c) adjust the target power at the same rate irrespective of the extent of frequency deviation, a segmented droop control method is presented in Fig. 10(d), where a smaller droop coefficient is used to restore the small frequency deviation and a larger droop coefficient is used to restore the large frequency deviation [54]. Thus, it better utilizes the rapidity and flexibility of power electronic components [52].

However, since the droop control gradually stops regulation when the frequency is reaching the dead-band, the droop control methods in Fig. 10(c)∼(d) may result in a dynamic equilibrium or chattering at the edge of the dead-band. To address this issue, a fast and slow frequency control is presented in Fig. 11(a), in which the fast frequency control regulates once every 20 grid cycles with a step change followed by the droop characteristic out of the dead-band, and the conventional droop control regulates once every 400 grid cycles within the dead-band [67]. The step change in fast control is able to sharply restore the frequency back to the nominal value, but it may also cause oscillation when the active power is suddenly changed. To restore the active power slowly in the process of system frequency recovery, the frequency emergency control is presented in Fig. 11(b) [68], in which the active power jumps sharply according to the red line in emergency control when the system frequency exceeds the dead-band and restores gradually back to the dead-band through the droop characteristic. As an important index in the updated grid codes, ROCOF is considered as an additional triggering signal for the frequency emergency control in Fig. 11(b) [68], [69], in which the emergency control is activated when ROCOF is above its threshold and the droop control is activated when ROCOF is below the threshold. To segment the emergency control even more precisely, a two-stage emergency control scheme employs multiple step changes based on multiple ROCOF thresholds [69].

DERs are able to operate without pre-curtailment when energy storage systems (ESS) are integrated [70], where $P_o = P_{MP}$ since the power reserve is provided by ESS [71], but it is only economically preferable to add ESS when ESS prices fall below energy prices. In wind power system, the upward reserve service can also be provided by the rotational inertia. To date, there has been little detailed estimation of inertial response requirements in the United States, but the Electric Reliability Council of Texas has studied the potential need to procure inertial response services [72]. The kinetic energy stored in the rotating mass of blades, shaft and generator rotors can be extracted through DER inverter control and then delivered into the power grid to arrest the ROCOF [73]. The pre-curtailment and reserve services provided by ESS is measured in units of power, whereas the inertia provided by wind turbines is measured in units of energy, or GW-seconds.

3) FREQUENCY REGULATION BY INERTIA EMULATION

As discussed before, the frequency support is needed because of the lack of system inertia. Therefore, recent trend of research is oriented in providing the synthetic inertia to increase the stiffness of the frequency characteristic under high penetration of renewable DERs [74]–[78]. The inertia emulation by wind turbines has been achieved by changing the grid-feeding active power and has been mandated by HQ and IESO in Canada [79]. ESS such as ultracapacitors and batteries are also able to serve as the inertia emulation, and the virtual inertia generated by the DC-link capacitors of DER inverters has a great potential due to its low cost [80].

The DER inverters provide synthetic inertia with the frequency-derivative-based approach [74]–[78], i.e., injecting/absorbing an active power that is proportional to the derivative of the grid frequency to mimic the inertia of convention synchronous plants. The fundamental principle of inertia emulation is mathematically described by:

$$P_e = kf_n \cdot \frac{df}{dt} \tag{1}$$

where P_e is the emulated power, k is the inertia coefficient, f_n is the nominal grid frequency, and df/dt is the ROCOF. Different with the frequency regulation by active power control that the active power reference is determined by the frequency deviation, inertia emulation sets the active power reference according to the ROCOF.

V. POWER SYSTEM SUPPORT FUNCTIONS—VOLTAGE AND FREQUENCY RIDE-THROUGH

Since a large number of DER disconnections under grid contingencies due to islanding protection in traditional grid codes can cause power outage and cascading failures, it is essential that DERs remain connected during voltage and frequency transients to limit the amount of load shedding and to prevent system from collapse. Thus, the modern grid codes also include dynamic regulation such as voltage and frequency ride-through requirements, which will be detailed in this section.

A. VOLTAGE RIDE-THROUGH REQUIREMENTS

Voltage sags and swells happen often each year due to abrupt increase or decrease in sources and loads, lasting for half a cycle to a few seconds. When the sag or swell percentage is too high, it is regarded as a grid fault and the DER inverters need to be disconnected from the electric power system according to traditional IEEE Std. 1547-2003 and UL 1741-1999 standards developed for low penetration level of DERs [13], [81]. Under high penetration scenarios, disconnection of a large number of DERs from the grid will further deteriorate the power system conditions and cause more severe events like power outage. Therefore, maintaining grid reliability and stability presents a greater challenge to the network operators nowadays, and updated grid codes such as IEEE Std. 1547-2018 [15] include voltage ride-through criteria that require the grid-tied DER inverters to remain in operation for a certain period of time before a grid fault is cleared [82], [83]. The voltage duration profile with voltage ride-through requirements is shown in Fig. 12, where the border lines vary from country to country with regard to the voltage drop depth, fault time, voltage recovery time and final voltage magnitude [20], [83]–[89].

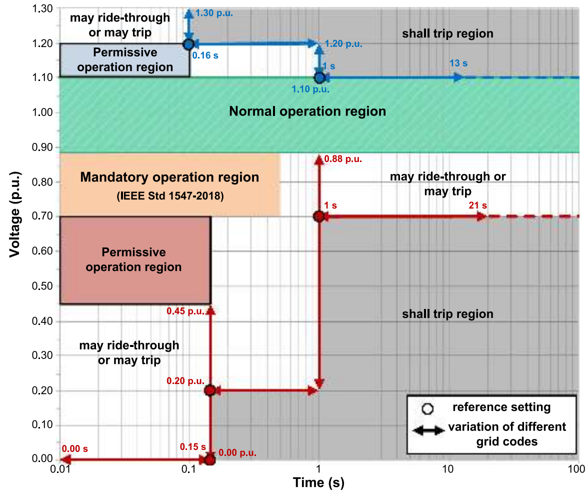

FIGURE 12. Voltage ride-through requirements.

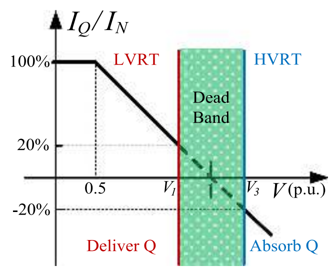

FIGURE 13. Reactive current injection requirement.

In addition to remaining connected during grid faults, DERs are also required to inject/absorb reactive power for the grid voltage recovery, represented as the ratio of reactive current I_Q to rated current I_N as shown in Fig. 13. The basic principle is same as the voltage regulation by reactive power control: DER inverters absorb reactive power when the voltage is swelling and inject reactive power when the voltage is sagging. The reactive power support requirements such as the ratio of reactive current to voltage sag/swell, maximum required reactive power also vary from country to country [87]. Moreover, low voltage ride-through (LVRT) occurs at a wider range than high voltage ride-through (HVRT) as the disturbance tolerance for voltage swells is much smaller than that for voltage sags.

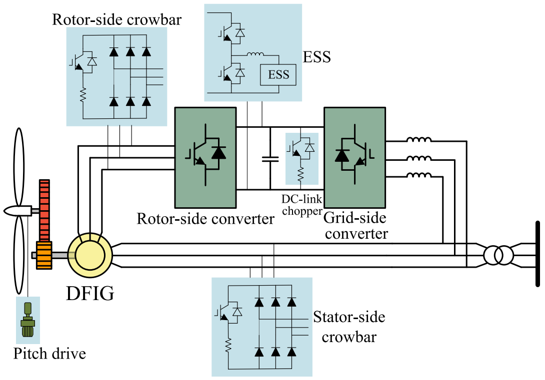

FIGURE 14. Schematic diagram of a DFIG-based wind power system.

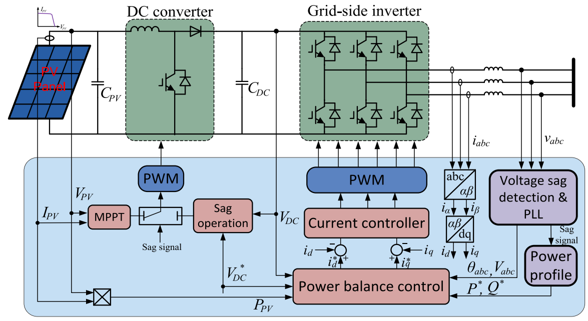

FIGURE 15. Schematic diagram of PV system.

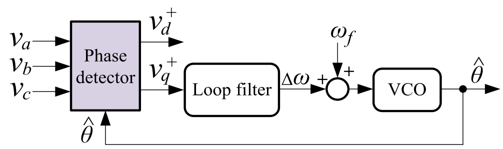

FIGURE 16. Basic structure of a three-phase PLL.

B. LOW-VOLTAGE RIDE-THROUGH TECHNIQUES

According to the voltage ride-through criteria, the wind and PV converters shall maintain synchronism, continue to exchange current and energize the electric power system during temporary voltage sags. The majority of transmission system operators (TSOs) have similar grid codes for wind and PV systems, but the LVRT techniques for wind and PV systems are different due to their different system characteristics [90]. Wind power systems generate AC power through rotational generator, in which the output power shall not be changed rapidly due to the inertial response; instead, PV systems generate DC power through PV panels, in which the output power can be changed suddenly.

Wind power system LVRT techniques can generally be classified as passive methods using auxiliary devices and active methods using control strategies [91], [92]. The auxiliary devices in passive method include pitch drives for blade pitch angle control, crowbar for limiting rotor voltage and current, energy capacitor system similar to the connection of crowbar, energy storage system and static var compensator (SVC), as shown in Fig. 14 for a doubly-fed induction generator (DFIG)-based wind power system [91]. Since the additional devices increase system cost, the control strategies in active method aim to regulate rotor voltage and current to meet the LVRT requirements, which include non-crowbar method, robust controller in α-β stationary frame, virtual rotor resistance, PI controller with a resonant compensator, vector-based hysteresis current controller, and sliding control [92]. As the effect of control strategies is limited as compared with hardware modifications, the combination of topological changes and control strategies is the trend in LVRT of wind power systems [93], [94].

PV systems have inherent self-protection characteristic according to the I-V curve characteristic, so the hardware protection circuits are not as necessary as that in wind power systems [90]. In order to satisfy LVRT requirements for a three-phase PV system as shown in Fig. 15, control strategies are applied 1) to detect voltage sags and synchronize with faulty grid voltage through sequence separation method (SSM)-based phase locked loop (PLL) under asymmetrical voltage sags; 2) to inject proper current to the grid by current controller during fault transients. The LVRT capability can generally be improved from two parts of the control system: a) grid voltage detection and synchronization, b) grid current control and power balance.

1) VOLTAGE DETECTION AND SYNCHRONIZATION

Detection of voltage sags and synchronization with the grid play a pivotal role in continuing to exchange current during voltage faults. Voltage detection methods are usually integrated with SSMs into the algorithms of PLLs. As the most commonly-used synchronization method, PLLs are reviewed in literature [95]. The basic structure of a three-phase PLL is shown in Fig. 16(a), which generally contains a phase detector, a loop filter and a voltage-controlled oscillator (VCO). The main difference among the PLLs is dependent on the phase detector, which is consisted of voltage detection and SSM. Three-phase PLLs utilize Park transform and SSM for extracting positive sequence components under unbalanced conditions, while single-phase PLLs usually utilize single-phase dq-transform without SSM as they do not have asymmetrical problems [96]. Three-phase PLLs can also be implemented by three single-phase PLLs to obtain the amplitude and angle of each phase at the cost of complicating the control system [97].

Traditional voltage detection methods, such as root-mean-square (RMS) voltage detection method, peak voltage detection method, discrete Fourier transformation method and dq-transformation method in conventional synchronous reference frame PLL (SRF-PLL), are able to calculate the grid voltage sag depth with half to one fundamental period delay under balanced and undistorted voltage conditions. But the calculations become inaccurate when the grid voltages are unbalanced or distorted by low-order harmonics [98]. Then some other voltage sag detection methods based on their

TABLE 2. Detection Time of Various PLL Methods Under Unbalanced Grid Fault

PLL	DDSRF-PLL	DSOGI-PLL	EPLL	VSPF-PLL
Time	12ms	11ms	80ms	25ms
MAF-PLL	LSRF-PLL	MRF-PLL	MCCF-PLL	FASRF-PLL
20ms	60ms	40ms	20ms	10ms

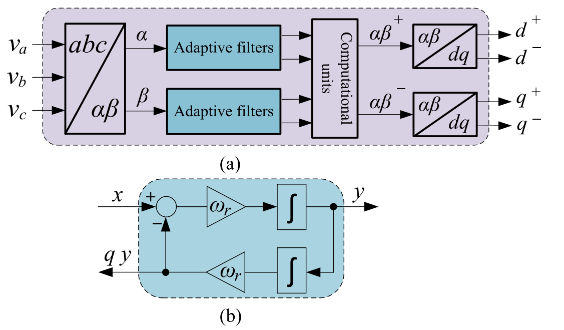

FIGURE 17. Basic structure of: (a) sequence separation; (b) SOGI.

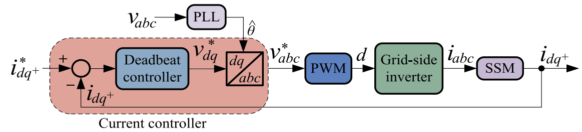

FIGURE 18. Basic structure of current controller.

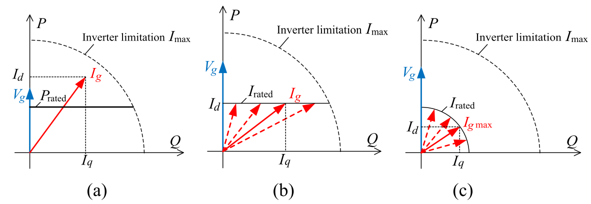

FIGURE 19. Single-phase LVRT techniques: (a) constant average active power control, (b) constant active current control, (c) constant peak current control.

own PLLs are proposed, which include decoupled double (DD)SRF-PLL [99], dual second-order-generalized-integrator (DSOGI)-PLL [100], synchronous observer-aided preprocessing (SOAP)-PLL [101], enhanced PLL (EPLL) [102], variable sampling period filter (VSPF)-PLL [103], moving average filter (MAF)-PLL [104], low-pass-filter (L)SRF-PLL [95], multiple reference frame (MRF)-PLL [105], multiple complex-coefficient filter (MCCF)-PLL [106] and SRF-PLL with fast and accurate voltage detection modules (FASRF-PLL) [98]. The detection time of these methods under ideal (balanced and undistorted) grid conditions and non-ideal conditions (unbalanced and distorted) are shown in Table 2.

Since the occurrence of symmetrical faults is extremely rare in power systems as compared with asymmetrical faults [107], SSMs should be added to PLL to resist the disturbances of negative sequence and harmonics to obtain more accurate amplitude and phase angle for synchronization and control. As shown in the structure of SSM in Fig. 17(a), the voltages in static frame are transformed into synchronous rotating frame first, where one sequence component appear as a DC quantity and the other appears as a double-line frequency quantity; then various filters are used for cutting off the double-line frequency quantity and extracting the desired sequence. The adaptive filters can be notch, band-stop and low-pass filters, or second-order-generalized-integrator (SOGI) as shown in Fig. 17(b). Notch, band-stop and low-pass filters have a slow transient response with narrow bandwidth [102], [108]. Delayed signal cancellation, also known as T/4 delay method, responds to sag transients much faster with a quarter cycle period (T/4) intrinsic delay, and needs memory space to store the T/4 data. Only harmonics in specific order and phase angles can be eliminated [108]. Differentiation method adds a derivation step to remove the intrinsic T/4 delay in the T/4 delay method, and its response is faster but more sensitive to harmonics [109]. SOGI quadrature-signals generator (SOGI-QSG) in DSOGI-PLL does not require extra memory space and can reject the disturbances from harmonics, while its response time is longer than the T/4 delay and differentiation methods [100].

2) CURRENT CONTROL AND POWER BALANCE

Apart from the voltage sag detection and synchronization, DER inverters also need to deal with the over-current issue caused by abrupt grid voltage drop and the DC-link voltage surge caused by power unbalance. The block diagram of a current controller is shown in Fig. 18, where the deadbeat controller can be replaced by the commonly-used proportional-integral (PI) controller or proportional-resonant (PR) controller in some control strategies [110]. Under unbalanced voltage faults, the grid currents become asymmetrical and the DC-link voltage contains second-order ripple due to power unbalance. To improve the performance under asymmetrical faults, a vector current control with feedforward of negative-sequence grid voltage (VCCF) is used to compensate the negative sequence components of the unbalanced grid voltage and achieve sinusoidal and symmetrical grid currents, at the cost of DC-link voltage oscillating at double-line frequency [107]. Dual vector current control (DVCC) takes the negative sequence of unbalanced grid voltage into consideration to inject a constant real power to the grid, with the tradeoff between constant DC-link voltage and unbalanced grid currents [108]. In addition to the current control strategies as classified in [111], [112], a continuous mixed p-norm algorithm-based PI controller is proposed in [113] in order to improve the controller performance in replacement of traditional PI controller.

In case of single-phase power systems, an orthogonal signal generator is used to decompose the active and reactive components, and a single-phase *PQ* theory-based method is adopted to meet LVRT requirements [96]. Constant average active power control and constant active current control are presented in Fig. 19 to maximize the energy exchange during LVRT [114], where they have possibility of overcurrent when the required injection of reactive power is also fulfilled. Similarly, a constant peak current control is shown in Fig. 19(c),

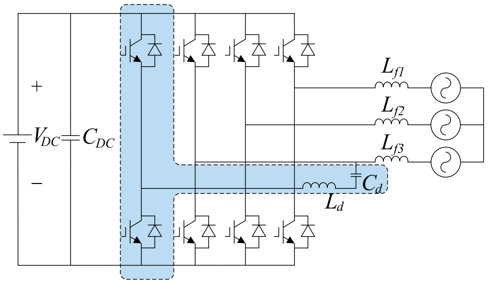

FIGURE 20. Power decoupling circuit for an unbalanced three-phase system.

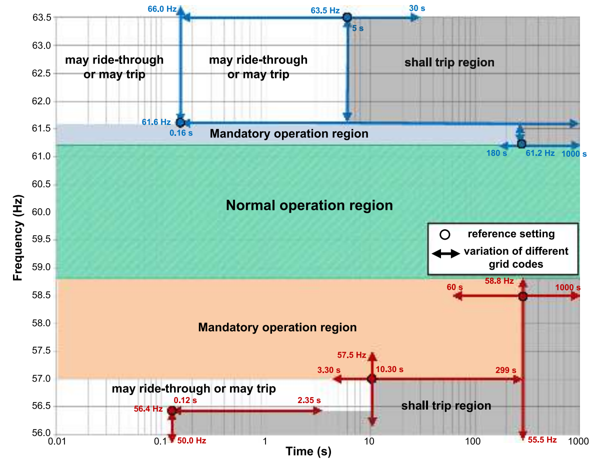

FIGURE 21. Frequency ride-through requirements.

in which the peak of the injected grid current is kept constant and active power is reduced to inject sufficient reactive power during LVRT [114]. Combining the three control strategies together, the thermal optimized control strategy is proposed in [115] to achieve a constant junction temperature of power devices and thus improve the energy utilization and overall reliability.

Power balance control, or DC-link voltage control, is often integrated into the above control strategies and aims to maintain power balance and stable DC-link voltage [84]. As described above, the contradiction between grid current quality and DC-link voltage oscillation cannot be solved simultaneously under unbalanced voltage fault. Traditional power balance control methods measure the DC-link voltage and compare it with a constant reference through a PI controller, but the grid voltage sag worsens the grid current quality because of the lower modulation index. Then an adaptive DC-link voltage control is proposed to improve the grid current quality by adjusting the DC-link voltage accordingly through the first stage control [97]. A multi-mode scheme is also presented in [116] for the first stage to switch among different modes to maintain balanced power under fault conditions. Moreover, the inherent power imbalance in single-phase systems and unbalanced three-phase systems can be mitigated or eliminated by adding power decoupling circuits as shown in Fig. 20 [117].

C. HIGH-VOLTAGE RIDE-THROUGH TECHNIQUES

During a transient voltage swell caused by load shedding or fault clearance, DER inverters are still required to stay online during and after the grid voltage fault if the voltage is within the HVRT region shown in Fig. 12. DER inverters are also required to absorb certain amount of reactive power according to Fig. 13.

Auxiliary devices and control strategies employed in HVRT are very similar to those in LVRT, where the objective during HVRT is mainly reducing the grid voltage instead of supporting it. Static synchronous compensator (STATCOM) and dynamic voltage restorer (DVR) have been used in [118], [119] to compensate the voltage swell by drawing reactive power from the grid or injecting voltage in series with the load. The DC-link chopper circuit in Fig. 14 is used to limit the DC-link voltage by consuming active power through the resistor to avoid crowbar ignition during HVRT [120], [121], and a superconducting magnetic energy storage is proposed in [122] to enhance the dynamic performance of DFIG-based wind power system and voltage ride-through capability. Control strategies such as improved vector control [123] and variable-band vector-based hysteresis current control [124] are proposed to guarantee the grid current quality during HVRT. As the voltage swell can cause over-modulation of the grid-side inverter, flexible DC-link voltage control is proposed to adjust the DC-link voltage through the first stage control [125]. Furthermore, virtual impedance control strategy has also been proposed to enhance the HVRT capability by limiting the rotor voltage magnitude in a wind power system [126].

D. FREQUENCY RIDE-THROUGH TECHNIQUES

The sudden loss of generators or loads may lead to severe frequency sags or swells, which last from 0.1s to a few seconds. When the frequency deviation is large, it is regarded as a grid frequency fault by the traditional standards, and the DER inverters shall be disconnected from the main grid [13], [81]. Under high penetration of renewable DERs, interconnection standards and grid codes nowadays include frequency ride-through criteria that require the grid-connected DER inverters to remain in operation during frequency transients to prevent cascading failures and system collapse. The clearing time settings for frequency ride-through requirements is shown in Fig. 21, where the general idea is to ride through the brief and deep sags/swells, or longer but shallower ones. The borderlines vary from country to country, and from province to province in Canada [20]. Unlike the voltage ride-through operation, frequency ride-through does not have overvoltage or overcurrent problems under frequency deviations. Then the operation of DER inverters under frequency ride-through is to maintain synchronism with the electric power system and, as applicable, modulate active power to regulate the frequency conditions as specified in Section IV-B.

During temporary frequency disturbances, DERs shall detect the deviated grid frequency, check with the requirement

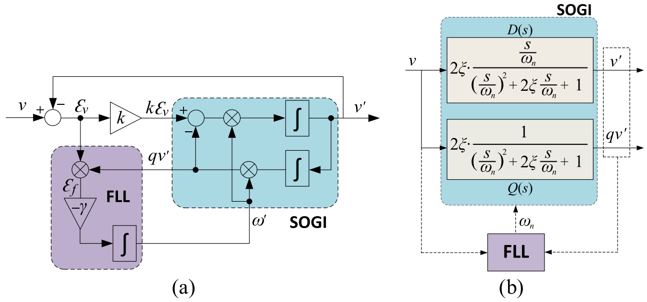

FIGURE 22. SOGI-FLL: (a) block diagram; (b) equivalent structure with resonance-based controllers.

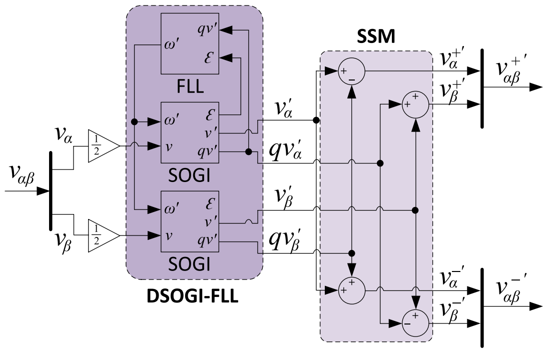

FIGURE 23. Block diagram of DSOGI-FLL.

for the protection signal, synchronize with the grid through PLL, and inject current to the grid. To ensure the frequency ride-through operation, the most important part is the grid frequency detection and synchronization. The frequency detection methods are usually integrated into synchronization methods such as PLLs and frequency-locked loops (FLLs).

Various PLLs have been discussed in the LVRT section about the voltage detection and synchronization, and PLLs with advantages of dealing with unbalanced grid faults are the preferable choices under grid faults. However, when providing the synthetic inertia through frequency derivative, PLLs will either introduce high-frequency noise or instability issues as compared with FLLs [76]. Moreover, PLLs generally synchronize with the phase of the input signal through a PI loop filter, so when synchronizing with frequency jumps, PLLs need to have a higher-order controller and slower response as compared with FLLs. The block diagram of a SOGI-FLL is shown in Fig. 22(a), where the SOGI can be represented and designed by two resonant transfer functions, as shown in Fig. 22(b) [127]. In three-phase applications, there exist α-β components and positive-negative sequences. Then a similar approach to DSOGI-PLL in [100], but using FLL instead of PLL, is presented in Fig. 23 [128]. In this case, a set-up consisting of two SOGIs and one FLL (DSOGI-FLL) provides the signal to SSM on the α-β reference frame. Besides the simple solution of DSOGI-FLL, multiple SOGI-FLL (MSOGI-FLL) is presented in Fig. 24, which makes the system more frequency-adaptive based on a harmonic decoupling network consisting of multiple SOGIs and an FLL. MSOGI-FLL not

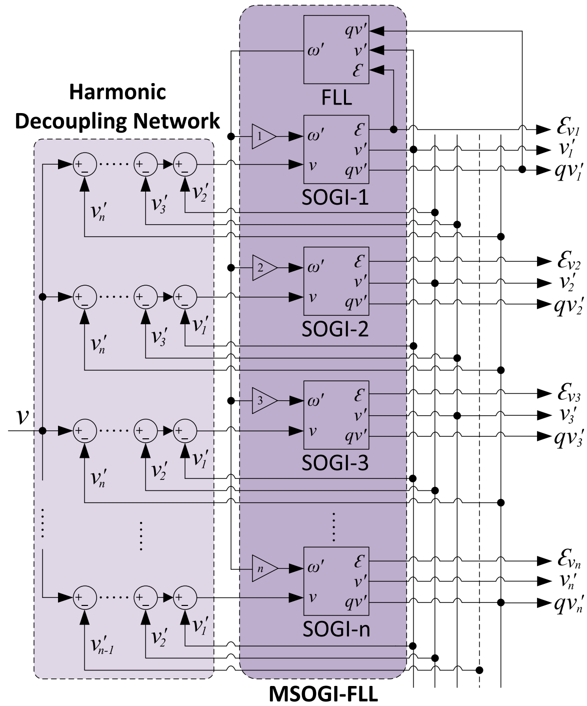

FIGURE 24. Block diagram of MSOGI-FLL.

only estimates the positive- and negative-sequence components of the power signal at the fundamental frequency but also other sequence components at harmonic frequencies.

Other synchronization methods like self-synchronized controllers also present robust performance that is not affected by the grid parameters. For example, a three-sample based PLL-less hysteresis current control of a grid-connected single-phase inverter for an active distribution system in [129] shows an improved performance and easier implementation during frequency swings as compared with the conventional SOGI-PLL. A decentralized control of series-connected PV-ES inverter in [130] achieves self-synchronization without communication and regulates the grid frequency with virtual inertia functionality.

VI. EMERGING TRENDS ASSOCIATED WITH DER DEVELOPMENTS

A. DER MODELING FOR BPS ANALYSIS

With increasing DER penetration, utilities have observed and experienced some serious impacts of DERs on the BPS [131]. Traditional DER impact analyses focus more on the injected THD level at the inverter output and feeder hosting capacity, voltage profile, protection at distribution system level. There is a demanding need from the transmission utilities to model the transient behaviors of DERs for BPS planning and operation analyses [132] at different timescales from hourly, minutes to seconds. Power system transient stability analysis looks into system behavior under large disturbances, under which the inverter fault ride-through capabilities help support grid voltage or frequency recovery.

Three different approaches can be pursued. The first approach is integrated transmission and distribution modeling and simulation in one framework. All the resources have to be modeled at the same timescale and the same type/precision, either static or quasi-static phasor model or dynamic model. This integrated system model can be very complex requiring heavy computation or advanced solver. The second approach is transmission and distribution co-simulation. The transmission system can be modeled in phasor form and simulated at a larger time step, while the distribution system including DERs can be modeled in details and simulated at a smaller time step. At the transmission simulation time step, interfacing data exchange involves phasor-to-waveform conversion and vice versa. When the interest is only at the transmission level, this approach suffers from lengthy detailed distribution simulation while the transmission simulation has to pause and wait for interfacing node updating data. Hence in the third approach, the aggregated DERs are modeled together with all the loads at the load bus where the distribution system is connected to the transmission network. Only transmission-level simulation is performed with dynamic DER aggregation modeling.

In recent years, the U.S. electricity sector is shifting from reliability to resilience as the major risk management measures after several major natural extreme events. Resilient grid modeling becomes crucial and DERs are known to play roles supporting grid resilience. Appropriate DER modeling is required and still under exploration for the purpose of grid resilience modeling.

B. SMART INVERTERS WITH NEW FUNCTIONALITY

Conventional DER grid integrations are through grid-feeding inverters, which are controlled to feed the maximum power available from the DERs in most cases and deenergize the grid once the grid is in abnormal conditions or power outage. With more and more DERs connected to power grid, utility is calling for DER inverters to support grid in an active manner rather than staying away. The latest IEEE Std. 1547-2018 and distribution grid codes such as California Rule 21 require the inverter based DERs to provide new control and protection functions both autonomously and by smart grid communications. Industries have used the term of “smart inverters [10], [133]” to describe this revolution.

Initially, smart inverters were mainly used for solar PV inverters with control functions of fault ride-through, grid voltage support, and reactive power compensation. As technology advances, the true meaning of smart inverters has been extended beyond the original definitions. The motivations are to address the challenges of power grids with decentralized system structures. Although those can be approached at different hierarchical levels and different time scales, the lower the level it is addressed, the faster the issue will be resolved with the least cost. This rationale requires more intelligence and functions for smart inverters to be able to provide a wide range of grid services, alleviate system control and protection burden, and better integrate with overall grid operations. In [11], such smart inverters are defined to offer five integrated system functions, which are integrated system control functions (e.g., grid-forming and regulation capabilities), distributed system stabilization functions (e.g., virtual inertia and damping provisions), integrated system protection functions, integrated sensing and measurement functions, and integrated cybersecurity functions.

C. GRID SERVICES AND TRANSACTIVE CONTROL

Utility power systems provide basic services including generating capacity, energy supply, and power delivery. To ensure reliable operation of interconnected power systems at transmission level, ancillary services are necessary, such as reactive power and voltage control, loss compensation, scheduling and dispatch, load following, system protection, and energy imbalance, as identified by USA Federal Energy Regulatory Commission (FERC). Before 1992, the power industry was regulated and vertically structured and these ancillary services were provided as non-commercial services. As power industry is deregulated and restructured, ancillary services become commercialized in the deregulated market. The deregulation has also made possible for independent power producers and distributed generations as well as any type of DERs in the distribution system to generate power and provide grid services.

To facilitate DERs to provide grid services, transactive energy framework and transactive control strategy are developed in recent years. Service-oriented architecture has been used in software design. There is trend to apply the same concept to the Electric Grid of Things (EGoT), which connects all the DERs including responsive loads. In the EGoT framework, the grid operator does not control the DERs directly and instead operate in a decoupled manner using an interface called energy services interface (ESI), while different DERs are bidding for the required grid services offered by the utility. Interoperability and plug-and-play are main goals for such an energy services interface. Currently standards serving for this purpose are under development and some relevant standard examples are IEEE Std. 2030.5 and OpenADR.

D. TOWARDS ELECTRONIC POWER GRIDS

Electric power systems are traditionally predominated by large synchronous generators and relatively slow electromechanical dynamics. Accordingly, system frequency is established by the well-known power-swing equation and load frequency control is based on power balance. In recent decades, power electronics have emerged in both low-voltage distribution systems for DER interconnections and high-voltage transmission systems including high-voltage DC (HVDC) and flexible AC transmission systems (FACTS). With the recognition of energy efficiency and fast controllability, power electronics-based grid devices, such as distributed power flow controllers, solid-state circuit breakers, solid-state transformers and substations are stretched into medium-voltage distribution grids, while new wide bandgap semiconductor devices and modular multilevel converters are used to provide direct medium-voltage grid access without using regular bulky transformers. Furthermore, variable-speed drives and LED lights are emerging on the load side. Essentially, power systems are moving towards electronic power grids.

Despite all the benefits, the increasing penetration of power electronics will also create new harmonic oscillation and stability issues as well as system control challenges. The control philosophy is in a transition from traditional centralized control structure into more decentralized or even distributed fashion. The smart inverter control functionalities presented in this paper will support this mega trend for autonomous and secure operation of electronic power grids.

VII. CONCLUSION

This paper provides an extensive overview of the development and evolution of the control algorithms in power system support functions by DERs. With increasingly recognized DER benefits and values such as enhanced controllability and grid resilience, electric power systems are transforming to a resource mix that relies less on coal and nuclear while integrating more distributed generation, energy storage and demand response resources. The global DER market penetration has been grown and will continue to grow based on market review reports. With the challenges and steps forward for reliably integrating more DERs, interconnection standards and grid codes as well as test criteria and procedures for power system support functions of DERs have been updated to cope with the expected multitudes of DERs to support the paradigm shift in distribution systems.

A variety of power system support functions, including voltage regulation by active/reactive power control, frequency regulation by active power control, voltage ride-through and frequency ride-through by improved synchronization and current control methods are explained in detail. The reactive power control in voltage regulation aims to achieve optimal voltage support with least increase of current stress. The active power control in frequency regulation compromises between the complexity of algorithms and frequency regulation. Voltage ride-through techniques, especially LVRT techniques, mainly depend on the grid synchronization methods and current control strategies to avoid over-current issues when the voltage dips or loses equilibrium. Frequency ride-through strategies rely on the frequency detection and synchronization algorithms. The merits and drawbacks of the control algorithms in each power system support function are briefly compared. Lastly, several key DER development trends such as DER modeling for BPS and integrated system functions are identified.

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