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TOPICAL REVIEW

Issues and Challenges of Grid-Following Converters Interfacing Renewable Energy Sources in Low Inertia Systems: A Review

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ABSTRACT The integration of renewable energy sources (RESs) is a key objective for energy sector decision-makers worldwide, aiming to establish renewable-rich future power grids. However, transitioning from conventional systems based on synchronous generators (SGs) or systems with a low RESs share presents challenges, particularly when accompanied by decommissioning large central generation units. This is because the reduction in inertia and system strength, traditionally provided by SGs, can lead to a loss of essential system support functions like voltage and frequency. While current converter technologies attempt to compensate for the grid support provided by SGs by enhancing converter capabilities, they still heavily rely on the presence of SGs to function effectively. These converters, known as grid-following (GFL) converters, depend on the grid to operate in a stable and secure manner. As the penetration of RESs increases, the efficacy of GFL converters diminishes, posing stability challenges in low inertia systems and limiting the integration of RESs. Therefore, it is crucial to reassess the existing GFL converter technologies, control mechanisms, and grid codes to understand their status and future requirements. This will shed light on the advancements and limitations of GFL converters, enabling greater RESs integration and grid support independent of SGs. This paper aims to provide an up-to-date reference for researchers and system operators, addressing the issues and challenges related to GFL converter technologies, control systems, and applications in low inertia systems. It serves as a valuable resource for facilitating the transition towards future systems with 100% RESs penetration scenarios.

INDEX TERMS Grid-following converters, low inertia systems, renewable energy sources, weak grids.

I. INTRODUCTION

Nowadays, the integration of renewable energy sources (RESs) such as solar photovoltaic (PV) and wind energy into the power systems is further accelerated to assist in achieving cleaner, less costly, and sustainable energy production. Based on the international renewable energy agency (IREA) [1] and the national renewable energy laboratory (NREL) [2] reports, the global renewable generation capacity has increased by 9.1% in the end 2021, where solar energy capacity has raised

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by 19%, and wind energy experienced a 13% increase in the installed capacity compared to 2020. Also, IREA and NREL reports [1], [2] stated that solar and wind energy will be the primary energy sources in the world by 2025, when 60% additional capacity from them would be installed globally. The transition towards high RESs penetration is vastly impacted by the environmental challenges, while economic and political issues have put more emphasis on such transition [3], [4], [5], [6], [7]. For instance, when wind sources are considered, the amount of power generation depends on the climate system and wind conditions like wind speed, which varies with time [3], [4]. Moreover, several other issues must be considered when RESs are installed into the power grid, including feeder and regulation issues, nature of control used, cybersecurity-related challenges, and the technology used for interfacing such resources to the grid. Feeder and regulation issues include topics on voltage instability, reverse power flow, feeder losses, harmonics, thermal line limits, and frequency issues. In addition to the challenges related to the security of supply, the dynamic modeling of the high penetration of RESs, dispatch, and scheduling problems adds more challenges on transition to high level of RES in power systems [6].

Achieving high penetration of large scale RESs would result in low inertia, which is identified as a crucial challenge in future power systems. In this regard, several issues must be taken into considerations when operating the system at high RESs penetration scenarios. For instance, ensuring stable voltage and frequency under all operating conditions is a must. High RESs targets require addressing and mitigating challenges such as: decrease of the system's inertia, the reduction in system transient stability margins, lack/excess of reactive power in certain location of the grid, voltage-dip propagation, frequency fluctuations, etc. [8], [9]. Based on the grid codes available in different countries, the system must be able to ride through the faults by providing reactive power required for voltage stability and system recovery. Besides, maintaining stability and security of future power systems with high RESs penetration, the system's reliability must be ensured as well.

Another key aspect that may result from the extensive integration of RESs into the grid is represented by the system strength reduction. Grid strength is defined as the ability of the power system to operate stably and to withstand all abnormal conditions that occur in the grid system [10]. This is typically characterized by the low short circuit level and the high equivalent grid impedance. In case of a weak grid, the higher risk of voltage instability is noted, but of course, other stability types such as transient stability margins will be adversely impacted. The concern regarding power system instabilities arise when the grid strength reduced [10], [11].

In practice, the grid strength not only impacts the system at the points of RESs connection, but also it affects the operation of the other components and devices in the grid. For instance, when a voltage sag occurs on the grid, the level at which such voltage sage would propagate through the network is strongly dependent on the system strength. Also, the proper operation of some system components such as capacitor banks are sensitive to the system strength and the short circuit level. A reduced system strength might cause maloperation of such components leading to voltage instabilities. Moreover, the reduced system strength, i.e., due to reduced short circuit level, would also result in a decreased sensitivity of protective devices as well as efficacy and efficiency of power system protection [12], [13], [14], [15], [16].

Considering the above-mentioned issues in future power systems with reduced system strength, operation of conventional converters interfacing RESs, utilizing grid-following (GFL) converters, would be more challenging. This is because GFL converters' control depend on the grid to operate in a stable and secure manner. This can be provided in systems with higher strength (i.ds. higher fault levels), however in a weaker network dependency voltage to reactive power and frequency to active power increases significantly, hence the voltage and frequency of the grid may not be stiff enough to ensure safe and secure operation of GFL-based RES. One of the most crucial system strength metrics is a short circuit ratio (SCR[1]), which highly affects the dynamic behavior of the GFL converter and acts as a grid weakness indicator [17]. As a result, GFL-based RES in a weak connection (e.g., SCR$<$3) may face more instances of instabilities, as detailed more in [18].

In addition, the line voltage affects the commutation between the switches in the line-commutated converter (LCC) used for GFL-based RES integration. The line voltage will be more susceptible to disturbances in weak connection circumstances which may result in low-inertia systems, including valve commutation failure, overvoltage from load rejections, frequency resonances, and voltage instability [19]. GFL converters use phase-locked loop (PLL) controllers, which track the magnitude and angle of the grid voltage, as they are non-synchronously coupled sources. In low inertia systems where the connection is usually weak, PLL may not be able to function properly during the weak connection. The study in [20] states that it is challenging to operate the PLL at low SCR and that, under such circumstances, a high gain is needed for adequate dynamic coefficients. This implies that GFL-based RES utilizing PLL might not be able to ride through the faults properly in weak networks under all the operating conditions [21].

Based on the above, conventional GFL- based RES might not be able to allow us to transit towards high penetration of RESs in future power systems, especially when displacing large synchronous generators (SGs). Therefore, it is crucial to reassess the existing functionalities of GFL converter technology, control mechanisms, and grid codes to understand their status and future requirements.

The remaining part of the review paper is organized as follows. Section II describes the effect of increased

[1]The SCR is defined as a ratio of the short circuit power at the PCC to the rated power of the converter side [33].

penetration of RESs and the low system strength. The GFL converter is introduced in more details in Section III from the structure containing the PLL part, principle of operation, and the control strategies used. The grid codes and GFL requirements are reviewed in Section IV. Issues and challenges of GFL converters such as the PLL related challenges, synchronization problems, voltage/frequency stability issues in weak grids are summarized in Section V. In Section VI, possible improvements, and suggestions available in literature are introduced including enhanced GFL functionality, self-synchronized PLL, inertia and fault level support and grid forming converter (GFM). Section VII concludes the work.

II. LOW INERTIA SYSTEMS AND WEAK GRIDS: OVERVIEW

In a power grid, inertia refers to the kinetic energy stored in rotating generators. This inertia is created by numerous synchronized generators, all spinning at the same frequency and in synchronization. An illustration of this concept can be seen in Fig. 1, where traditional generators are interconnected through electromagnetic forces depicted as chains. The presence of these electromagnetic chains allows each individual generator, while spinning and connected to the grid, to contribute to its overall inertia [22].

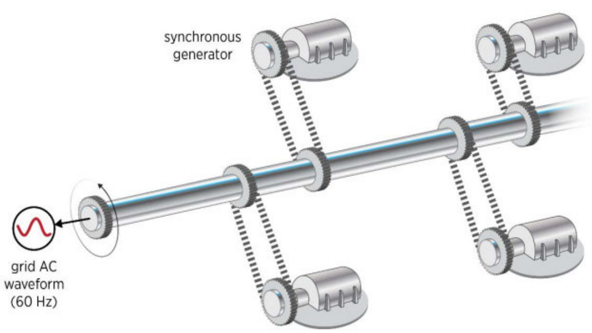

FIGURE 1. The concept of inertia contribution of synchronized conventional SGs [22].

As a result of the large increased penetration of RESs that utilize power electronic interfaces (i.e., converters), the grids lack the system's inertia causing different technical issues. Such reduction would be significant in those scenarios accompanied with displacements of large conventional SGs.[2] Note that this change not only results in reduced inertia in the grid but also the decrease in short circuit level, causing reduced system strength (i.e., weak grids). Consequently, several challenges may appear in future power systems, such as the difficulty of achieving frequency stability [23], [24], [25], voltage instability, and maloperation of the protection system [26], [27].

[2]Acknowledging the conventional GFL converters do not generally provide synthetic inertia This is not the case especially with GFM technology as discussed in Section VI .

The power grid can be classified into a strong and weak power grid where a strong power grid can withstand most sudden changes in operating conditions, such as: power demand variation and fault occurrence, as the voltage and frequency stays within acceptable limits and stable operation. On the other hand, a weak grid is more sensitive to any sudden changes in operating conditions, which may lead to a significant voltage and frequency variations resulting in an unstable system. According to the literature, multiple metrics and definitions have been proposed to quantify the strength of the system. Some references, such as in [28] and [29], define a system strength as a voltage's sensitivity to change in system condition and fault level in the location, while in [8] defines this as a frequency's sensitivity and system's inertia to the change in active power. A sensitivity of voltage variation with respect to the variation in active and reactive power (dV/dP and dV/dQ) is used to distinguish between the strong and weak grids weak grid in [15].

Concerning the connection of RESs, where the dynamic frequency and voltage stability of grid-connected RESs are not independent from grid strength, the IEEE1204 standard characterizes the weak grid based on its static and dynamic performance [30], [31]. Typically, a simple measure known as a short circuit ratio (SCR) is usually employed to indicate the system strength where RESs are connected [11], [32]. The SCR is defined as a ratio of the short circuit power at the PCC to the rated power of the converter side [33]. From the definition, when the rated power of the converter *increases* or the transmission impedance increases, the SCR will reduce resulting in a weak grid connection. To distinguish between the strong and weak grid connection, the SCR at the connected RES must be calculated. A SCR of greater than 5 indicates a strong grid, while the SCR below 3 indicates the weak grid. SCR below 2 indicates a very weak grid according to the IEEE standard 1204-1997 [10], [17], [34], [35], [36]. The system strength can be classified based on the SCR value, as shown in Table 1 [37], [38].

TABLE 1. The system's strength classification based on SCR values.

Symbol	Quantity
$SCR > 3$	High
$2 < SCR < 3$	Low
$SCR < 2$	Very low

The operation of the system in the weak grid (SCR<3) may cause several issues, such as; frequency resonance, voltage instability, and overvoltage from load rejections. This would make operation of controllers and the PLL utilized in converter-interfaced RESs mode difficult in such weak grid conditions [37], [39], [40]. In addition, it may cause increased cascading failure resulting from wider-area undamped power oscillations, deeper voltage dips, wider voltage sag propagation, and slower voltage recovery following a contingency

TABLE 2. Issues faced in grids of low inertia and reduced system strength.

Issue	Findings	Refs.
Frequency Response	• The frequency response is more susceptible to increase wind/PV generation due to the lack of inertial support. • Increased the system's sensitivity to the disturbance. • Increased in ROCOF and frequency deviation. • Caused load shedding or tripping generator. • Low-frequency oscillatory stability issues.	[23]-[25]
Voltage Stability	• The voltage is sensitive to power variations at low fault levels (weak grid). • A sudden increase in active/reactive power causes a large voltage variation and instability. • Overvoltage cascading due to voltage fluctuations or overvoltage occurrences. • Integrating RES with a weak grid may cause voltage instability. • Deeper voltage dips • Wider voltage sag propagation • Slower voltage recovery	[26], [27], [37], [39], [40]
Cascading failure	• It results after fault-induced voltage reduction and when there is a voltage fluctuation in the converters. • The reduction in the inertia of the power grid would lead to load shedding and cascading failures.	[16],[41], [42]
Mis-operation of the protection system	• The increased ROCOF resulted in protective relay tripping. • Over-current protection is the most likely to be affected in low inertia systems due to low short circuit levels which might not be adequate to ignite the relays. • If the difference between the currents is very small, it may not be detected by the differential protection. • This ratio of voltage to current is affected by significantly different volumes of SGs at peak and minimum demand and may challenge the operation of distance relays.	[27], [29], [43]-[46]

event [16], [41], [42]. On the other hand, the reduced inertia would also increase the rate of change of frequency (ROCOF) and frequency deviation [43], [44], [45]. The high rate of ROCOF causes a trip on the relay, and a high-frequency oscillation may cause unintentional load shedding. Table 2 summarizes other challenges that may occur due to low inertia and low SCR.

III. GRID FOLLOWING CONVERTERS

A. STRUCTURE AND BASIC CONTROL OF GFL CONVERTERS

The most straightforward representation of GFL is shown in Fig.2. Based on that; it can be seen that the GFL acts as a controlled current source parallel to the high impedance Zc. The working principle of the GFL control is shown in Fig.3. The GFL concept is used mainly in distributed energy resources as well as grid -connected RES in the recent years [47], [48]. It consists mainly of three parts; outer voltage control loop, inner current control loop, and PLL, as depicted in Fig.3. These control loops are responsible for different control actions, and they can be summarized in voltage support, current tracking, and grid synchronization. The GFL structure aims to achieve a regulated converter current with a fast dynamic response. The PLL is the key to regulating the output power by measuring the grid voltage phase and magnitude.

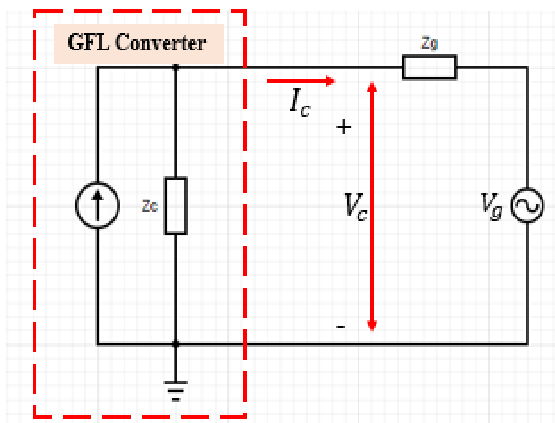

FIGURE 2. Structure of GFL converter [47].

In other words, the PLL needs a reference value to follow the phase angle and magnitude. The PLL uses the voltage measurement at the PCC as the input, then the frequency and phase angle are required to perform the current control loop. The output power of the converter is controlled using one of the available grid support functions. The inner current loop must be controlled to be faster than the outer voltage loop. Increasing the number of the GFL converter disbalancing conventional SGs will decrease the number of strong

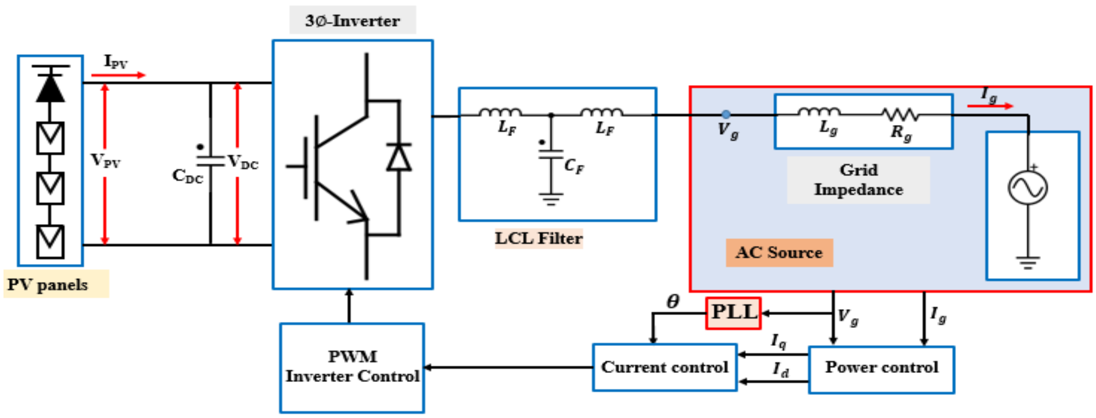

FIGURE 3. Control structure of GFL converter [49].

TABLE 3. Control types in the gfl converter.

Control type	Control objective
Outer voltage control loop	It generates the reference values to the inner current control loop. It also regulates active power on q-axis and the PCC voltage on the d-axis.
Inner current control loop	The objective is to achieve fast regulation of the output current.
PLL	The objective is to extract the estimated voltage angle and magnitude at the PCC to synchronize the plant with the grid.

voltage sources that can provide inertial response. Based on the GFL converter's control objectives summarized in Table 3, the GFL converter's performance depends on the control topology used, the strength of the grid, and tuning control parameters.

Although the availability of steady-state and dynamic voltage support, primary frequency support as a function of droop and inertia response, and fault ride through in GFL are vital for future grids, these supports lose their effectiveness when the power grid is weak.

The GFL's structure has issues summarized as phase-locked loop problems, high-frequency stability problems such as harmonics resonance [50], [51], [52] and so on detailed in Section V. Different control methods are illustrated in the literature to solve these problems and enhance the GFL's output, such as PQ control [53], [54], current-controlled droop control [54], [55], droop-based multi-loop control [56], and current-controlled virtual synchronous generator (VSG) control [54], [57]. The PQ-control, current-controlled droop control, and droop-based multi-loop control were introduced to improve the frequency response while they have many limitations, such as no grid support, poor stability, and suffer from frequency oscillation problems in the weak grid, and they cannot be in stand-alone operation. The current VSG method was introduced to support the power grid under any grid conditions. However, it still has stability and frequency oscillation problems when integrated with the weak grid and cannot operate in stand- alone mode [54], [55], [58].

B. PLL AND GRID SYNCHRONIZATION

The PLL is the negative feedback closed loop system that can effectively synchronize the power converter with the grid. The PLLs are widely used for grid synchronization for both single and three-phase systems due to the simplicity of implementation and robustness under different grid conditions [59], [60], [61], [62], [63]. The PLL structure is implemented in synchronous reference frame (SRF), as shown in Fig.4, which consists of three main parts: 1) a phase detector (PD), 2) a loop filter (LF), and 3) voltage-controlled oscillator (VCO). The abc-to-dq transformation in three-phase system is used to track the phase information. The PD part contains the phase error signal information of the input signal and the PLL output [61]. While the LF produces a control signal that is used to determine the system dynamics response performance and stability of the PLL [64], [65], the VCO is used to generate a synchronized signal with the grid [66].

There are many types of the PLL available in the literature, which is different in the type of PD used. Based on the available literature, the PD can be designed using the power and quadrature signal generation (QSG) as well. The power based PLL (pPLL) is easy to implement, however it suffers from the inherent double frequency oscillation in the estimated grid parameters. The PD based on QSG has a better performance compared with pPLL, but the performance depends on generation of an appropriate orthogonal signal of SRF transformation especially when used for single-phase system. In general, the performance of the PLL depends on the implementation of the PD and the LF parts. Three phase PLL structure used in most GFL is shown in Fig.5, where V_{PCC} is the three-phase voltages that is measured at PCC. In the GFL converter, this voltage must be converted into $dq0$-reference frame ($V_{PCC-dq0}$). The q-axis voltage (V_{PCC-q}) is used as input to the PLL.

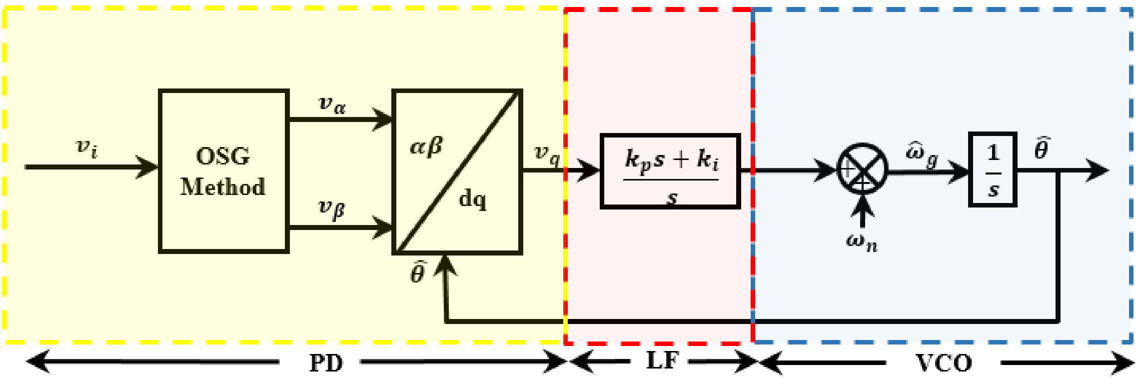

FIGURE 4. The implementation of the PLL structure in SRF [67].

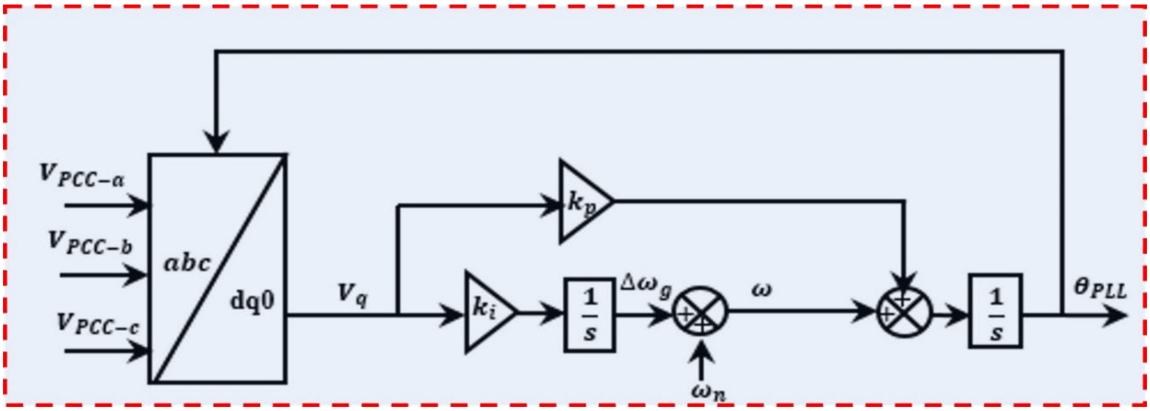

FIGURE 5. Simple structure of three-phase PLL used in most GFL converter where the V_q Is the control signal and the output signal is the phase angle (θ_{PLL}).

Based on that, the estimated phase angle of the PLL (θ_{PLL}) is calculated using (1) [68].

$$\theta_{PLL}(t) = \int \left(\omega_n + \left(k_p + \int k_i \Delta\omega_g(t) V_{PCC-q} dt\right)\right) dt \tag{1}$$

Note that the angular grid frequency (ω_g) is given as in (2):

$$\omega_g = \omega_n + \Delta\omega_g \tag{2}$$

where ω_n is the nominal grid frequency, and it is equal to $2\pi 50\ rad/s$, and $\Delta\omega_g$ is the deviation in the angular grid frequency from its nominal value during the disturbance. Besides, k_p, k_i are the proportional and integral gains of the PI-controller gains used in the PLL.

Based on Fig.5, the voltage at PCC in q-axis frame can be written using the following grid parameters; grid voltage (V_g), grid current (I_g) and the equivalent impedance from the grid side (Z_g) as given in (3).

$$V_{PCC-q} = V_{PCC} \sin\left(\theta_g - \theta_{PLL}\right) + I_g Z_g \sin(\theta_z) \tag{3}$$

where θ_g is the grid phase angle and θ_z is the angle between (V_g and I_g). The difference between the grid phase angle and the PLL's output phase angle is given in Eq. (4).

$$\delta = \theta_g - \theta_{PLL} \tag{4}$$

Several forms of the PLL have been reported in the literature in recent years, where the main difference is the type PD used such as; time-delay based PLL(TD-PLL) [69], [70], [71], [72], all-pass filter (APF) [41], [73], [74], [75], inverse park transform (IPT) [76], [77], second-order generalized integrator (SOGI) [78], [79], [80], moving average filter (MAF) [81], [82], [83], low-pass filter(LPF) [84], [85], [86], [87], etc. The PLL structure used with the GFL converter should have a fast dynamic response (less settling time, less overshoot), accurate grid parameters estimation under any disturbances conditions, simple structure, and robustness during the voltage dip and harmonic presence on input AC signal [88], [89]. The PLLs listed in Table. 4 have varying levels of complexity in design. Each type used a different structure to create a fictitious quadrature signal for transferring information into the dq-frame. This paper focuses on the most common structures used in single-phase and three-phase PLLs. The work in [90] utilizes the arbitrary delay signal cancellation (ADSC) with variable-length time delay PLL (ADSC-based VLTD-PLL) to achieve synchronization with a DC-offset rejection and a fast dynamic response. However, the use of 4 time delay in VLTD-PLL restricts the design. This limitation is solved in [67] by utilizing two arbitrary delay operators to enhance the dynamic performance of DC-offset rejection. However,

TABLE 4. The summarized comparison for recent plls available in the literature.

PLL's type	Advantages	Disadvantages	The type of disturbance rejected accurately			Refs
			Double frequency oscillation	DC-offset	Harmonics	
ADSC based VLTD-PLL	Fast dynamic response	Memory requirement is increased.	Yes	Yes	×	[90]
Modified FIR-EPLL	Fast dynamic response.	Memory requirement is increased.	Yes	Yes	×	[67]
SOGI based VLTD-PLL	• The implementation complexity is decreased. • It enhances relative stability. • It simplifies the control design. • It has a fast dynamic response.	The use of the fixed-frequency SOGI block requires to use of phase and voltage amplitude correction.	Yes	Yes	×	[91]
Adaptive CDSC-PLL	It perfectly rejects the DC-offset and harmonics with a fast dynamic response.	The use of frequency adaptation increased the complexity and cost of implementation.	Yes	Yes	Yes	[92]
Non-adaptive $DSC\text{-}PLL_1$	• It has a fast dynamic response. • The use of non-adaptive operators can decrease the cost of implementation.	Amplitude and phase correction is needed	Yes	Yes	Yes	[92]
Non-adaptive $DSC\text{-}PLL_2$	• It has a fast dynamic response. • The use of non-adaptive operators can decrease the cost of implementation.	Amplitude and phase correction is needed	Yes	Yes	Yes	[92]
MAF-EPLL	Remove the even order frequency ripple and DC offset	• Two MAF blocks are required in inner of amplitude and frequency loops which increased the implementation complexity. • The MAF's window length and the gains of amplitude, frequency, and DC offset compensations must be designed correctly to enhance the dynamic performance	Yes	Yes	Yes	[93]
Outloop dqDSC-PLL	• The operation of the CDSC operation is more straightforward. • It is very easy for digital implementation	The phase estimation phase and amplitude unbalanced conditions produces the offset error and frequency adaptation is required.	×	×	Yes	[94]
Inloop dqDSC-PLL	It has a fast dynamic performance, higher bandwidth, and higher design flexibility	• The phase estimation phase and amplitude unbalanced conditions produces the offset error and frequency adaptation is required.	Yes	Yes, but limited for only DSC_2	Yes	[95]

TABLE 4. *(Continued.)* The summarized comparison for recent plls available in the literature.

		• The use of CDSC in in-loop complicated the controller designs. • It suffers from discretization errors in practical implementation.				
Adaptive CDSC-PLL	It can be estimated the phase accurately under both amplitude and phase unbalanced conditions	The time constant of LPF add a restriction to the PLL	Yes	Yes	Yes	[96]
DSOCCFdc based MAF-PLL	• The MAF block is used to block high-order frequency harmonics . • The DSOCCFdc is used to completely reject the DC-offset and to separate the positive and negative sequence from the input grid voltage	• The appropriate parameters should be selected to ensure good dynamic performance and stability. • The DSOCCFdc can only suppress the high-order harmonics but cannot completely block them. • Placing the MAF block in the inner loop complicates the system's design.	Yes	Yes	Yes	[97]
Non-adaptive $\alpha\beta$-MAFPLL	It improves the dynamic performance	The MAF's window length effects on the dynamic response performance and it should be selected carefully	Yes	Yes, but limited	Yes	[97]
dcDNANF based-PLL	It increases the phase tracking speed and dynamic response, enhancing stability	There is no information about the control strategy used, which affect the cost of implementation, and dynamic and steady-state performances.	Yes	Yes	Yes	[98]

the memory requirement is increased. Also, the concept of the ADSC operator is applied to the second-order generalized integrator PLL(SOGI-PLL) in [91], showing accurate and fast detection for DC-offset rejection. However, there is no information about the ability to reject the harmonics.

The work in [92] introduces three different structures based on cascaded delay signal cancellation (CDSC) with frequency adaptation and without frequency adaptation; adaptive CDSC-PLL, non-adaptive DSC-PLL$_1$, and non-adaptive DSC-PLL$_2$. The number of CDSC operators used depends on the type of harmonics need to be rejected. The use of CDSC operators without frequency adaptation decreases the system's complexity. Nevertheless, they require amplitude and phase compensation.

Another type of enhanced PLL with a moving average filter (MAF-EPLL) is introduced in [93] to remove the even order frequency ripple and DC-offset rejection. Nonetheless, two MAF is required in the inner loops of amplitude and frequency compensation. The accurate grid parameter estimation under the even harmonics and DC-offset required an accurate selection of the MAF's window lengths and amplitude, DC-offset, and frequency compensation.

The work in [94] utilized two versions of the PLL used the delayed signal cancellation (DSC) in the dq-frame operator to eliminate any specific harmonics achieving accurate and fast dynamics performances and high control bandwidth when the input grid voltage is significantly polluted by unbalanced and harmonics. The cascaded DSC (CDSC) operators remove the group of specific harmonics. The first PLL version can remove the symmetrical odd and even harmonics up to the 22nd order. The second version can remove all symmetrical and asymmetrical harmonics up to the 30th order except -15th and +17th orders. Both versions have a simple structure, and their digital implementation is easy. However, the phase estimation of the two versions under the phase and amplitude unbalanced condition produces the offset error and frequency adaptation is required. Besides, the cost of implementation is high. The principle of CDSC operators in dq-frame is extended to be used as an in-loop filtering stage in [95]. To improve the response time, the PID-LF is used instead of PI-LF which can result in a fast dynamic performance, higher bandwidth, and higher design flexibility. However, the phase estimation of the two versions under the phase and amplitude unbalanced condition produces the offset error. In addition, it suffers from discretization errors in practical implementation because of the use of non-ideal sampling frequency.

For accurate phase estimation under the unbalance amplitudes or phase angles in the three-phase system, the work in [96] utilized an adaptive cascaded delay signal cancellation (CDSC) to generate the balanced three-phase amplitude by removing the odd and even grid input's harmonics, DC-offset, and the negative effect of the frequency variation. Five CDSC operators are used to eliminate all the lower odd and even harmonics up to 20. Accurate phase estimation is ensured by using one synchronous reference frame PLL (SRF-PLL). The estimated frequency from the output of PLL is filtered using the 1^{st}-order low pass filter (LPF). However, the time constant of LPF in a feedback path should be selected to be equal to or greater than the time constant in a forward path which adds a restriction to the PLL. Compared with the work in [94] and [95], the work in [96] can be estimated the phase accurately under both amplitude and phase unbalanced conditions, and the cost of implementation is reduced.

The combination of the dual second-order complex coefficient filter with DC offset rejection capability (DSOCCFdc) and moving average filter (MAF) is introduced in [97]. The MAF block is used to block high-order frequency harmonics while the DSOCCFdc is used to completely reject the DC-offset and to separate the positive and negative sequence from the input grid voltage. The appropriate parameters should be selected to ensure good dynamic performance and stability. However, the DSOCCFdc can only suppress the high-order harmonics and cannot completely block them. Also, placing the MAF block in the inner loop complicates the system's design.

In [97], a simple non-adaptive $\alpha\beta$-MAF acts as a pre-filter to improve the dynamic performance and simplify the controller's design. A phase error compensation removes any phase offset when there is a grid frequency variation. The proposed structure of the $\alpha\beta$-MAFPLL is implemented by a cascade of complex comb filter and complex backward-difference integrators. This structure does not introduce a phase delay into the feedback loop, while improving the dynamics performances. The MAF's window length is selected to be half of the nominal period. But, in general, when the MAF's window length decreases, the speed of the response increases, affecting the filtering capability such that the DC offset cannot be rejected.

As mentioned above, fundamental frequency negative sequence (FFNS), harmonics, and the DC-offset components may reduce the PLL's accuracy. In [98], the novel adaptive notch filter (NANF) is introduced to eliminate the FFN and extracts the fundamental frequency positive sequence (FFPS). Another two structures are proposed in [98] adopting a dual NANF (DNANF). The first structure is proposed to reject the DC-offset, which is called dcDNANF, and the second structure is a combination between dcDNANF and the two cascaded DSC operators in the dq- frame whose delay length is 4 and 24, which is called a novel hybrid filter. The second structure separates the FFNS and FFPS of the input voltage and eliminates the high-order frequency harmonics. The proposed methods improve the dynamics performance by increasing the phase tracking speed and dynamic response, enhancing stability. However, there is no information about the control strategy used, which affects the cost of implementation, and dynamic and steady-state performances.

IV. GRID CODES AND REQUIREMENTS OF GFL

The integration of RESs into the power grid is increasing rapidly worldwide. The grid code requirements for connecting RESs to the grid are updated continuously by the transmission system operators (TSO). These requirements are used to ensure reliable and stable grid performance. The grid code requirements differ from one country and another, and their severity depends on the RESs penetration level. The main objective of developing the grid codes is to ensure a stable and regular operation for the grid [99].

Grid support is necessary when the GFL converter is integrated into weak grids or low system inertia due to increased PLL challenges, and frequency variation [17], [100], [101], [102], [103]. Different control ancillary services and droop control functions are integrated with the RESs to support the grid in terms of voltage and frequency, such as: steady-state voltage support through reactive power management, FRT and dynamic voltage support, current-controlled droop control, current-controlled virtual synchronous generator, frequency-watt control, fast frequency response (FFR), simulated inertia and primary frequency support regarding droop and inertial responses [12], [40], [55], [100], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123]. In addition, several regulations are developed to account for the power quality measures when integrating RESs [110], [124], [125], [126].

A. VOLTAGE SUPPORT AND FAULT RIDE THROUGH

One of the crucial requirements needed to support the voltage in any grid conditions is a fault level which dictates sensitivity of the grid voltages and frequency to the reactive and active power variations. A low fault level is a weak grid with a high sensitivity of voltage variation with respect to the variation in active and reactive power (dV/dP and dV/dQ) while a high fault level is a strong grid with a low sensitivity of voltage variation with respect to the variation in active and reactive power (dV/dP and dV/dQ) [37]. In other words, it represents the ability to provide system's stability support by injecting reactive current during the short circuit [124].

In low fault level conditions, problems such as instability, oscillations, and collapse may occur more. For example, the effect of voltage sag can mitigate by injecting an additional reactive current to ride through and support the grid voltage. The voltage profiles depend on the duration and the depth of the voltage sag [125]. The work in [126] states that the converter should be able to remain connected in very deep sage for at least 0.15s, considered a short interval. It should also remain connected in moderate voltage sag during 2s, considered a long time. Also, the work in [126] states that the reactive/active power ratio is an essential issue in voltage support requirements. Only reactive power is injected in deep voltage sag, while active and reactive powers must be injected in shallower ones.

Dynamic voltage support requires during a fault occurrence from the converter-based RESs to support the voltage by injecting reactive current in a positive and negative sequence system that is directly proportional to the voltage change between the faulted and pre-faulted situations [127]. Some strategies are introduced in the literature to improve the current quality, DC-link ripple voltage, and instantaneous active and reactive power [128], [129] in such situations. The dynamic voltage support depends on the system strength or the fault level, as discussed in above [130].

Voltage ride-through (VRT) is one of the essential requirements developed because of high RESs penetration into the grid to ensure stable operation and voltage support under abnormal conditions. The VRT can be classified into a low VRT (LVRT), zero VRT (ZVRT), and high VRT (HVRT) [99], [131], [132]. The work in [133] concludes that the VRT requires the RESs to link with the grid and provide auxiliary services such as; injection/absorption of the reactive current to ensure voltage and grid stability.

The LVRT is one of the essential requirements that must be considered for dynamics performance during any low voltage event caused by the faults in the grid. In the case of large-scale systems, the regulations require the renewable power plant (RPP) to withstand the operation during the fault occurrence. When the fault is cleared, the active and reactive power production should be recovered quickly because the voltage is reduced to less than 90% of the nominal voltage value [133].

ZVRT represents the worst-case of LVRT where the voltage is reduced to zero. Support voltage recovery and grid stability through reactive current injection are required in such scenarios [134]. The RESs are disconnected when the voltage is zero, while the voltage recovery differs from country to country, as stated in [131]. In practice, the chance of having a three-phase solid fault resulting in zero retain voltage during the faults is very slim, hence there is not much concern around these scenarios.

In the case of voltage swell, overvoltage in the power grid causes stability problems. So, the HVRT is required for stable operation. In USA's HVRT regulation, the RESs must stay connected and resist an overvoltage of up to 140% of their original value within 1 s. In comparison, Spanish and Australian HVRT rules requirements allow an overvoltage of up to 130% from the nominal value before disconnection from the grid [131], [135], [136].

The FRT is defined as a time against voltage characteristic that specifies the minimal requirement of the plant to ride through the fault in the event of a voltage dip. In the case that the voltage drops below the limit, the plant is allowed to be disconnected. After the fault clearance, the FRT requires a fast recovery for active and reactive power to their nominal values [172], [173]. The RESs must stay connected during the fault's occurrence and support voltage by injecting the reactive current. Each country has its own FRT requirement due to the difference in the RES penetration level and the size of generation units, and therefore they used different voltage-against-time profiles to define the FRT requirements [174]. Those requirements also define the reactive current injection requirement during the voltage dip conditions. The works in [175], [176], and [177] summarize that the injected reactive current value and the current injection speed can significantly impact the fault current dynamics as expected. The following factors: Fault detection time, measurement, and communication time, PLL response time, and the rise time of the injected current, can impact the reactive current injection speed, hence the dynamics of the future power systems. The UK grid code requires immediate current injection with an unspecific time delay [178]. The European Network of Transmission System Operators for Electricity (ENTSOE) requires injecting the current between (10-60) [179]. The speed of reactive current injection as a rise time must be within 100 ms, based on Ireland grid codes, within 20ms after a fault detection, and 30ms/60ms as a rise/ transient time based on Germany grid codes [174].

As introduced in German grid code requirements [137], the reactive current injection/absorption should be evaluated according to voltage drop or increase, respectively. If the voltage changes within ±10% dead band, the RESs still operate regularly, and no reactive current injection is needed. If the voltage exceeds this dead band period, the RESs should inject a reactive current. Based on USA standard [138], the RESs may inject or absorb 1%-10% reactive current when the voltage exceed ±15% dead band.

B. FREQUENCY SUPPORT

Different factors cause the grid frequency deviations, such as: power generation loss, the use of old power system generation, the use of RES power generators with a lack of grid support, the RES productivity with sudden interruptions, and high dynamics in solar irradiance and wind speed, as well as the load variability (which has been always the case even in traditional power systems) [139], [140]. The voltage-frequency variations are used as imbalance indicators between power generation and consumption. Based on grid codes requirement, the over-frequency requires reducing the active power, while in the case of under-frequency, the active power should be increased (subject to energy for power increase being available). The work in [139] proposes a new controller with frequency and voltage supports. The adjustable gradient controls the active and reactive power flow to ensure a transition between grid-feeding and charge grid-loading.

One type of frequency support is fast frequency support (FFS) addresses the frequency support capability of inertia-less generation units under the first few seconds of the significant power imbalance. The FFS can be classified into inertial response (IR), primary frequency response (PFR), and secondary frequency response. When the change in frequency causes a change in the rotational speed and kinetic energy of the generation units, this leads to a reduction in speed until the rate of frequency changes (df/dt) equals zero. This type is called inertial response although it is appreciated in conventional power systems inertial response is an inherent feature of rotating mass connected to SGs, while FFR intends to help the situation by a controlled response during that short 0.5 second imbalance between load and generation. The primary frequency response (PFR) adjusts the SGs' active power generation via the governor action until the balance between generation and consumption results in stable system frequency. Depending on the generation unit's characteristics, it reacts within a few seconds after the disturbance occurs (normally within 5 to 30s). The system frequency needs to restore to its nominal value using the secondary frequency response (SFR) using its automatic generation control (AGC) [141], [142], [143].

The effect of FFR on dynamic performance can be quantified using the following three indices [141], [144]:

- **Initial rate of change of frequency (ROCOF) (df/dt)** is a time derivative of power system frequency (df/dt)
- **A frequency nadir** is a minimum frequency value reached during a transient period depending on system inertia and PFR [144].
- **Steady-state frequency deviation** is a maximum frequency change at which the system is designed to be stabilized after a significant power imbalance depending on the total amount of PFR delivered at a specific time.

C. POWER QUALITY MEASURES

Power quality issues such as harmonics, flickers, voltage transients, and voltage unbalance are result of large-scale RESs integration. Harmonics distortion is a severe power quality issue resulting from the large integration of power electronics with RESs. Several regulations are developed by measuring total harmonics distortion (THD) to ensure a low level of distortion. Several available standards, such as; IEEE Std 519-201, IEEE 1547 Stds, and IEC standards, require THD to be less than 5%, while Romanian standards require a THD of a maximum of 3% for PV and wind plants integrated with the transmission system [131], [145], [146], [147].

Table 5 summarizes all ancillary control services integrated with GFL used in supporting the grid in term of the objective of use and the observations.

V. CHALLENGES AND MITIGATING MEASURES OF GFL CONVERTERS IN LOW INERTIA SYSTEMS

In this section, the operation of the GFL in weak grid conditions is discussed in terms of challenges and mitigating solutions. This covers issues related to voltage/frequency stability, the PLL's synchronization, and the grid support functionalities.

A. STABILITY CHALLENGES (VOLTAGE AND FREQUENCY)

One of the crucial challenges of using GFL converters is characterized by the instability that might be encountered when operating under weak grid conditions. The work in [13] introduces an efficient compensator to eliminate the negative impact of distributed virtual inertia (DVI) by supporting and keeping the system stable. Applying the DVI release energy preserved in DC-link capacitors to follow the frequency disturbance in the grid. A significant hurdle associated with utilizing GFL converters lies in the inability to replace all SGs and operate the system under 100% converter penetration scenarios due to the absence of a synchronization frequency source. Conversely, when such GFL converters are integrated with high penetration scenarios replacing SGs, it leads to diminished voltage and frequency regulation capabilities, consequently presenting heightened difficulties in managing fluctuations in AC voltage. Hence, issues in in synchronization and system instability are to appear in the grid [150]. To mitigate such problems, the low voltage ride-through (LVRT) or what is referred to as FRT capabilities of GFL are introduced as a solution for enhancing the stability problems in many grid codes such as the Irish grid [151].

One more issue that might be associated with the increased penetration of GFL converters is represented by the transient angle instability caused by the current limiter during the fault, potentially leading to the imbalance between the input and output power and instability issues. Several types of research are introduced to avoid transient angle instability issues. The work in [152] investigates the transient angle stability of paralleled SGs and virtual synchronous generators (SG-VSG) systems in islanded microgrids.

In that work, the transient angle stability is enhanced by decreasing the amount of reactive power.

The work in [68] investigates the effect of the nonlinear characteristics of the GFL converter on stability, especially in significant signal disturbance. That paper summarized that the GFL converter loses strength and stability in weak grid conditions.

The lack of natural inertia and the negative damping effect during the increased power electronics utilization in power systems may result in frequency fluctuations and system instabilities. The adverse effects of integration of GFL converters can be avoided using virtual inertia emulation control loop. The fast frequency response can be achieved in low-inertia systems by optimizing the virtual inertia for different dispatch points, such as system split and tripping of generators [153]. The work in [58] demonstrated that frequency stability of low-inertia systems using a virtual

TABLE 5. Ancillary control services integrated with GFL for grid-supporting purposes.

Ancillary control services	Objective	Findings and Notes	Ref.
		Grid Support Functions	
Voltage Support and Fault ride-through	It is required to support the voltage during a fault to avoid grid collapse.	a control method is required to manage the reactive power delivered during balanced/unbalanced conditions.	[106]-[108]
	It requires supporting the voltage during the fault where the reactive current injection in positive and negative sequences are directly proportional to the voltage's change between fault and pre-fault.	• It does not study the control and protection of the system under voltage sag/swell disturbances. • It is related to dynamics support without any frequency support function.	[106], [116]-[118]
	It requires a fast recovery for active and reactive power to their nominal values after the fault clearance.	• External devices such as reactive power injection devices, and energy storage devices should be integrated with FRT to improve performance.	[148], [149]
Primary frequency support	It requires ensuring dynamics grid support by reproducing a synchronous generating unit's power–frequency response.	• Oversizing of the rotating machine is recommended.	[106], [120], [123]
FFR	The quick and controlled contribution of active power depends on the frequency measured	• The fastest FFR increased the ROCOF value in a low inertia system. • Instability resulted from PLL inaccuracies during very fast transient response	[115], [121], [122]
Simulated inertia	This is a PLL-free frequency control method. Its more effective than FFR in arresting ROCOF	• The effectiveness is limited in the case of frequency nadir. • It is superior, especially for higher penetration of RESs.	[12], [115], [122]
		Droop Control Functions	
PQ control	It regulates each generation unit's active and reactive power using the reference voltage value.	• No inertia support capability. • Poor stability under weak grid conditions. • It cannot operate in stand-alone mode. • It induces a large frequency deviation under a small disturbance.	[40], [54]
Current-controlled droop control	It improves the frequency response by providing voltage-frequency (VF) control, or inertia supports for the power grid.	• No inertia support capability. • Poor stability under weak grid conditions. • It cannot operate in stand-alone mode	[55]
Current-controlled virtual synchronous generator	It improves the frequency response by providing VF, or inertia supports for the power grid.	• Poor stability under weak grid conditions. • It cannot operate in stand-alone mode	[113]
Frequency-watt control	It supports the frequency response in fast timescales by adjusting the converter output with the change in frequency.	• It cannot actively generate grid frequency when transitioning to islanded mode.	[114], [119]

induction machine (VIM) synchronization connected to the GFL converter ca be improved. The VIM is based on the emulation of the induction generator principles. This method ensures smooth start-up and synchronization with an accurate grid frequency, voltage, and power estimation. The work in [154] studied the effect of high-grid impedance on the system's stability under different disturbances. The outer DC-link and AC-side voltage control loops are introduced with a GFL converter to examine the stability performance for the large signal scale and under weak grid conditions. It was shown that stability depends on minimizing the DC-link control's integral gain while maximizing the integral gain of the AC-side voltage control. In this work, the overcurrent capability's advantageous property is achieved compared with the overvoltage capability, whose marginal advantage's impact.

The GFL converter required synchronization to be able to inject stable active and reactive power into the grid. A synchronverter, which acts as an ideal voltage source, is introduced in [155] to enhance the system's stability. The electrical distance between the power converter is taken into design consideration of that method due to easy implementation, the standard proportional resonant controller shows the best performance, especially in tracking negative sequences. This type of control does not depend on the synchronization scheme.

The conventional vector current control (VCC) is widely used with GFL converter to avoid the instability issues resulting from the positive feedback in the PLL. However, this type of control suffers from power limitation problems under weak grid conditions. A simple impedance reshaping method is introduced in [156] to enhance the GFL converter's small-signal stability, extend the system's stability range, and reduce the impedance model's negative resistance.

Since the GFL converter synchronizes with the grid through PLL, it can become unstable after the fault occurrence. Using the PLL frequency limiter slows down the phase change during a fault. However, it has a crucial impact on the system stability, contains errors in the PLL input, and then slows the overall system response.

B. PLL AND SYNCHRONIZING CHALLENGES

The development of fast semiconductor switches and the ability to implement using advanced and complex control enabled quick evolvement in designing cost-effective and grid-friendly converters. The power-electronic interface should be able to control the energy conversion and transmission and reactive power to minimize the harmonics distortion achieving a low-cost design, high efficiency, high reliability and tolerance for the failure subsystem component [157]. The extensive integration of power electronics-based devices is essential in modern power systems. It affects the power system operation, mainly when operating in the grid-following mode, causing power quality concerns. The excess reactive power, transients, power factor collapse, large current and voltage fluctuations, voltage sag/swell, notch, harmonics, noise, and DC offset are some examples of power quality disturbances [158], [159], [160], [161].

The power quality disturbances in the utility grid resulted from the sudden changes in the load, the lines switching, non-linear loads, faults, and the AC grid strength. It resulted in the digital equipment malfunctioning, unwanted tripping of protective relays and circuit breakers, and computer and microprocessor-based sensitive devices damaging [158]. In the case of integrating solar power into the grid, many synchronization problems may appear in presence of harmonics due to its structure. RES based on solar have different power outputs depending on solar power efficiency used for power production and the weather, causing power oscillations resulting in harmonics issues and frequency fluctuations. In the case of wind power, since the wind speed continuously changes, this causes voltage and frequency changes resulting in an unbalanced power supply and varying frequencies [161]. These disturbances must be monitored to mitigate their effect and alleviate significant system balancing and losses. The interaction between the power electronic converters and the weak grid impedance, the frequencies coupling, and the dynamic coupling strength increase the harmonics pollution and sub-synchronous interaction [162], [163].

PLL is the heart of the GFL converter synchronization and stable response in steady-state and after faults and failures in the network. The use of the PLL in synchronization is the most popular one. It is also found in many applications that require synchronizing the output grid parameters, such as: voltage phase, voltage amplitude, and frequency synchronization with the grid input. These applications can be summarized as synchronization and control the distributed generation systems, AC transmission systems, uninterruptible power supplies, high voltage transmission, sensorless AC control measurements, power quality instruments, and estimate harmonics, inter-harmonics, sequence components, and peak values. However, the PLL's dynamic performance strongly interacts with other parts, especially when the GFL is integrated into a weak grid and the unbalanced AC voltages during the fault caused second harmonic generation [67], [88], [89], [90], [91], [164].

The mutual interactions of inner-current loop and the parallel-connected voltage source converter (VSC) have a large influence on the synchronization stability [165]. The operation of the GFL in a weak grid with a low X/R ratio, droop controllers' interaction, lack of inertia, and power production/ consumption fluctuations may have a negative impact on the stability margin. So that, the PLL should be able to improve the dynamic stability and performance in reference tracking, disturbance rejection, frequency estimation and noise immunity [166]. Comparing the power electronic devices with SGs, under a sudden disturbance and a power imbalance, the SGs provide inertia inherently to support the power system. However, the power electronics devices (without any inertia emulation feature) reduce the inertia which cause high frequency nadir and ROCOF [167]. Also, the impact of power grid strength and the PLL is studied in [96], [162], [166], [168], [169], [170], [171], [172], [173], [174], [175], [176], [177], [178], [179], [180], [181], [182], [183], [184], [185], [186], [187], [188], [189], [190], and [191]. All available research related to PLL are based on the small-signal model, however the effect of the non-linearity must be considered, especially when the power grid is weak.

All PLLs mentioned above address the dynamical performances under unbalanced and distorted grid conditions. The fast and accurate tracking and good filtering characteristics have been considered in PLL designs in recent years. However, other points related to the PLLs must be taken into consideration as reported in Table 6.

As we can see, all PLL's design is based on the small-signal model and does not consider a large-signal model. In practical use, grid fault is one of the common large-signal disturbances and it is necessary to investigate whether the system is still stable in such circumstance. In [168], it is reported that frequency instability results when the VSC is connected to a weak AC grid. The works in [169], [170], and [171] concluded that the synchronization instability issues have resulted from the negative resistance behavior of VSC's impedance. In [172], the large-signal stability is related to two kinds of issues; the first is related to the existence of the equilibrium points, and the second is the transition process analysis and the size of the decelerating area. The work in [172] concluded that a grid impedance variation caused instability resulting from the non-existence of equilibrium points. Also, it is indicated that increasing the decelerating area according to the impedance angle and increasing the equivalent damping improves large signal stability related to the transition process. So that this work contributes to revealing the physical mechanism of the large-signal synchronizing instability in VSC-based power systems. The dynamic performance of the selected PLL interacts with the other part in a real converter system, especially when the converter is integrated into the weak grid. In the equivalent admittance model of the grid-tied converters the PLL induces the negative resistor, resulting in small-signal instability and output PLL sideband oscillations [162], [173].

The instability of PLL synchronization arises under high grid impedance or weak grid conditions. The work in [160] studies the impact of grid structure on the PLL stability of multi-converter systems. The stability margin of the PLL-based converter is strongly related to the grid admittance. The dynamics of the multi-converter system are coupled through the power network. Based on that, the proper placement of the converter affects the PLL stability. That work also concluded that the PLL-based VSC is stable only in the strong grid.

The increased penetration of RES into the power grid requires solving the issues related to power quality and stability of GFL-based RES. The LCL filter is integrated into a grid-connected converter to attenuate the switching harmonics, as in [174], while the capacitor current feedback with active damping is used to suppress the resonance of the LCL filter, as in [175]. The selection of the PLL with high bandwidth speeds up the dynamic response. However, it has a negative impact resulting in resonances appearing between the converter part and the grid [176]. In addition, it increases the negative real part of the converter's output impedance, which also affects the system's stability under the weak grid [177]. If the PLL's bandwidth is decreased, the PLL slows down, resulting in a long time to reach to its steady states [178]. The work in [179] introduces a new method to reduce the PLL's negative effect on the current controller of the weak grid due to robustness against the impedance variation. The controller in [179] is designed based on static stability constraints, phase margin and gain margin, and the impedance analysis of the converter to reduce the negative effect of the integrated PLL. The impedance shaping methodology is utilized in [180] to design the feedback gains and the state feedback control. The objective of the feedback loops is to suppress the oscillations and to decouple the PLL's operation.

The items listed here cause a limitation on the stability margins of GFL-based RES utilizing PLL, such as: low X/R ratio, droop controller's interaction, lack of inertia, and periodic fluctuations resulting from the heavy load and generation changes. The work in [166] is introduced to cover the gaps in different available PLLs, and to improve the robustness of PLL, its dynamic performance and stability, disturbance rejection, frequency estimation, and noise immunity issues. The mixed sensitivity loop shaping and the in-loop filtering are proposed to improve disturbance rejection and noise immunity of PLL in [166]. This PLL has the following advantages: robustness against grid impedance variation, weak grid connection, transients, and distorted grid conditions. PLL improves frequency estimation using the synthesis of virtual inertia.

New stability and power quality challenges appear when the large-scale power electronics-based system is integrated. The instability of harmonics occurs as resonances or abnormalities in the wide frequency range. The work in [181] proposes a systematic analysis of harmonic stability and effective system tool analysis to identify the oscillation mode.

Many researchers studied how the bandwidth of the PLL should be selected. The work in [182] suggested selecting the PLL's bandwidth not greater than the fundamental frequency. But, the work in [183] discussed selecting the bandwidth of PLL not greater than one-tenth of the current loop bandwidth. Comparing the works in [182] and [183], it can be seen that the effect of the current loop is neglected in [182]. Using the consideration in [182], the PLL does not cause any harmonic-frequency oscillations. The work in [192] designed the current loop independently and the coupling effect between the current loop and the PLL under the weak grid conditions was considered there.

The sub-synchronous resonance issue for GFL-based RES is mainly resulted from a weak grid's impedance interaction.

The impedance interaction results from the capacitive converter and inductive grid impedances in the weak grid. The work in [184] suggested suppressing this using an inertia PLL (IPLL). The objective of using IPLL is to give an optimization of the low-frequency impedance of the renewable system. Also, it was concluded that the IPLL enhances the stability in the weak grid and can accurately estimate the voltage phase at the PCC.

Small-signal stability issues may appear when the GFL-based renewable energy is connected to a weak grid. The grid impedance and PLL effect are considered in [185]. The work in [185] proposed a very simple and effective control method that ensures the stable system's operation when the SCR is equals 2 and can suppress the oscillation.

Assuming the grid at PCC has a large impedance (i.e. weak network), and the work in [186] proposed a robust PLL delay-based grid current feedforward structure to improve the low-frequencies magnitudes, resulting in low-order harmonics, which is lower than typical PLL. This implies the phase margin is enhanced, and the converter can be worked correctly by varying the grid impedance even if the SCR is equal or less than 3. The work in [187] intended to effectively suppress the low-order harmonics using a novel feedforward control method. As a result, the perturbations of PLL are mitigated, and weak grid stability is enhanced.

In [188], a new simple, and efficient method to transfer power from RES with a unity power factor in weak grid conditions is proposed. That work aimed to utilize an impedance compensator to correct the angle deviation of synchronous reference frame PLL (SRF-PLL). The PLL's angle is compensated by measuring the weak grid impedance to ensure a zero reactive power is injected into a weak grid. The non-linear analysis due to the damping characteristic of the PLL in the weak grid is studied in [189]. It was shown that the non-linearity of the phase detector of the PLL used resulted in a sharp drop in the damping ratio under the very weak grid condition. Also, the small-signal stability of the PLL under the grid strength variation is analyzed based on the PLL's damping effect analysis.

An adaptive PLL switches between the second and first-order PLL when the fault occurs or the transient cleans was proposed in [190]. The transient stability can be enhanced by increasing the damping ratio of the PLL used, as discussed in that work. Besides this, the proposed adaptive PLL enables the VSC to operate in steady state operation by estimating the voltage phase accurately under the fault occurrence.

The frequency variation or the converter's power output oscillation can cause grid instability problems in weak grid conditions. The influence of reactive power control (RPC) method on grid instabilities is studied in [191]. Also, the effect of the PLL's loop shaping on how the stability margin can be increased is shown in [191]. This work suggested reducing the PLL bandwidth can enhance stability. Moreover, reducing the bandwidth makes the PLL response slow. To solve this issue, the work in [191] suggested the feed forward voltage (FFV) to be used to ensure a fast PLL dynamic response. Table.6 summarize the issues in a GFL-based converter and how they can be avoided.

C. GRID SUPPORT ISSUES

As discussed above, the GFL converter faces stability and reliability issues. The GFL converters may not control their output frequency [38]. Besides that, some of the GFL's control challenges make the system sensitive to the grid variations due to zero-inertia characteristics (if no inertial emulation control mechanism is implemented) and the reduction of overall system inertia [193]. Due to sudden generation or load loss, inertia is needed to ensure stable operation of the grid, which measures how a system can ''ride through'' disturbances and maintain stable frequency operation. The lower system inertia results in a fast (ROCOF) and frequency variation [194].

1) FAULT RIDE-THROUGH (FRT) ISSUES

FRT's grid codes are required to ensure GFL-based RES operate in a stable mode, remain connected, able to recover the grid voltage changes, and avoid any overcurrent conditions during the faults [3], [195]. In GFL converters, the instability issues increase when a faulted AC grid imposes a very low-amplitude and unbalanced PCC voltage [172], [190]. The poor FRT performance of the power converter is generally driven by inaccurate estimation of grid voltage magnitude and angle. The FRT capability of GFL- based RES should be enhanced to meet the grid requirement, such as injecting a minimum 2% reactive current for every 1% change in the voltage [196]. However, such requirements might be onerous in weak networks and may cause instabilities. The work in [197] presents a comprehensive review to give insight into the limitations of available research on FRT capability and their ability to compensate the voltage sag/swell and limit the fault short circuit current. Several research in the literature intended to enhance FRT model of GFL- based RES to provide better grid support. For instance, a hybrid grid synchronization transition method implemented in the dq-current controller used for three-phase VSC, including phase and frequency estimation using both a second-order SRF-PLL (SO-SRF-PLL) and arctangent methods [198]. The transition between two synchronization techniques depends on the grid voltage conditions. The SRF-PLL method is used during normal grid operation and switched to the arctangent method during grid faults. This method reduces the loss of synchronization during normal operation. Additionally, it improves the LVRT operation achieving robust current controller dynamics in case of symmetrical and asymmetrical faults.

In [199], a superconducting fault current limiter (SFCL) is introduced to enhance the FRT capability when the permanent magnetic synchronous generator (PMSG) is connected to the AC power grid. The SFCL's objective is to minimize the generators and grid-side's power and decrease the

TABLE 6. Summarize PLL issues and the method used to avoid them in weak grid conditions.

PLL's Type	PLL issues	Suggestions and Mitigating Solutions	Ref.
Three-phase SRF-PLL	Instability related to grid impedance variation	×	[172]
Three-phase SRF-PLL	Small-signal instability, output PLL sideband oscillations and high grid impedance	They used a unifying approach to the impedance models of the grid-tied converters with the PLL dynamics	[162], [173]
Three-phase SRF-PLL	Switching harmonics	It used the LCL filter is integrated into a three-phase grid-connected converter.	[174]
Three-phase SRF-PLL	LCL filter resonance	It used the capacitor current feedback with active damping	[175]
SOGI-PLL and Inverse Park PLL (IP-PLL)	The resonance between the converter part and the grid	It used the second order generalized integrator PLL (SOGI-PLL) and the inverse Park transformation PLL (Park-PLL)	[176]
dq −SRF-PLL	The negative real part of the converter's output impedance	×	[177]
Three-phase SRF-PLL	DC-bus voltage control instabilities	It provided physical insights into impact of AC-bus voltage control on stability of DC-bus voltage control in grid-tied converter connected to weak grid	[178]
Three-phase SRF-PLL	The PLL's negative effect on the current controller	It used static stability constraints to design the current controller and the converter's impedance analysis	[179]
A novel PLL with in-loop LPF	Oscillation	It used the impedance shaping methodology to design the feedback gains and the state feedback control	[180]
A robust SRF-PLL with in-loop LPF	Low X/R ratio, droop controller's interaction, lack of inertia, and periodic fluctuations resulting from the heavy load and generation changes	It used the mixed sensitivity loop shaping	[166]
dq −SRF-PLL	The instability of harmonics occurs as resonances or abnormalities in the wide frequency range	It used systematic analysis of harmonic stability and effective system tool analysis	[181]
Three-phase SRF-PLL	Harmonic-frequency oscillations	It used the optimal selection for PLL bandwidth while the current control loop is neglected	[182], [183]
Adaptive CDSC-PLL and dqCDSC-PLL	Harmonic-frequency oscillations	It designed the current loop independently. The coupling effect between the current loop and the PLL under the weak grid conditions is considered	[96]
An inertial PLL (IPLL)	The sub-synchronous resonance issue	It used an inertia PLL (IPLL)	[184]
Three-phase SRF-PLL	Small-signal stability issue	It established the small-signal transfer function integrated model of the current control loop which ensures a stable operation without changing the control method.	[185]
A robust TD-PLL	Low-order harmonics	It used a robust PLL delay-based structure with grid current feedforward structure. It used a novel feedforward control method with PLL	[186], [187]
SRF-PLL with angle compensation method	Angle deviation of synchronous reference frame PLL	It used Impedance compensated with PLL	[188]
SO-linearized model of SRF-PLL	Damping characteristic of the PLL and the effect of the grid strength variation	×	[189]
Three-phase SRF-PLL with pre-filtering stage and First-order PLL	Transient stability characteristics	It used an adaptive PLL switches between the second and first-order PLL	[190]
Three-phase SRF-PLL	The instability resulted from the frequency variation or the output VSC oscillation	It used the PLL shaping and used two control loops; RPC and FFV.	[191]

overvoltage across the DC-capacitor link. The resistive type of SFCL is integrated into the grid to avoid any effect of the existence of the inductance part during normal and abnormal operations. It improves the LVRT capability by limiting the rising rate of the fault current using the additional resistance with PMSG inertia [200].

A bridge-type fault current limiter (BFCL) controller is introduced in [201] to effectively limit the symmetrical and unsymmetrical faults currents, hence improving the FRT, and the dynamics performance for a large-scale wind energy system. Based on the fault detection on the PCC, the BFCL controller inserts resistance and inductance during severe disturbance to limit the fault current. This method has used machine and grid-sides VSC controllers to ensure a constant capacitor voltage and extract/ inject the current to the grid, respectively. Also, the speed and active power fluctuations of the PMSG are decreased as a result of that approach.

During the fault occurrence, the extensive integration of wind power generation into the power grid results in various power quality issues, such as voltage variation and grid voltage instability, and requires actions to be taken so that the wind power generation remains connected to the grid. The work in [202] improved the LVRT capability using an artificial neural network (ANN) controller. In addition, the electrical spring was used there to inject the critical voltage and overcome voltage sag issues, to further enhance LVRT capability of GFL-based RES.

The work in [203] presents a coordinated control method to satisfy the FRT requirement and enhance efficiency during normal and abnormal grid conditions for wind based technologies. The gearbox controller with a variable ratio in that work effectively reduces the mechanical power and as a result decreases the rotor acceleration and instability.

Also, the increased circulating current (CC) in the modular multilevel converter can result in the following issues such as power losses, component overheating, voltage instability, and harmonics distortion. So, the CC must remain within the acceptable limit to ensure safe and reliable operation. The work in [204] introduced a communication-free FRT for offshore wind power plants to effectively mitigate the adverse impact of short circuit faults as a rise in variation in DC-link voltage. This structure can efficiently handle fault scenarios, such as three-phase, single-line-to-ground, line-to-line, and double-line-to-ground faults.

The work in [205] presented a new control method for FRT capability to enhance stability and reliability, especially in extensive photovoltaic (PV) system integration. The converter should be disconnected during the permanent faults when the current exceeds a specific limit during a particular time. Otherwise, it should remain connected and ride through the faults when the transient faults occur. The high overcurrent in a doubly-fed induction generator-based wind turbine (DFIG-WT) is produced in the case of voltage sag [206]. So, the DFIG-WT must operate without losing the grid synchronization to meet LVRT requirements during grid faults. The static synchronous compensator (STATCOM) with FRT is introduced to support DFIG-WT. An enhanced field-oriented control (EFOC) technique improves the transient and dynamic stability and the power flow transfer in the rotor side converter (RSC). However, the RSC's protection may not be available using STATCOM. The LVRT's behavior is studied based on different grid codes for the enhanced control method under different voltage sag conditions in [206], where the dual SOGI-FLL with positive and negative sequences are utilized to estimate the grid frequency.

Using the enhanced LVRT mechanism, the correct control of active and reactive power can be achieved. Some of the available methods used for FRT enhancement are summarized in Table 7 in terms of improvements and advantages made.

2) TRANSIENT STABILITY ISSUES

In the GFL control, the transient interaction between the PLL and the weak terminal voltage cause the loss of synchronization of the PLL, which can be responsible for the transient instability issue in the grid-connected RESs, especially during LVRT or after faults. In power grids with many VSC generating units, the grid's inertia is decreased, resulting in increased frequency stability issues [207]. Several types of research are available to study transient stability enhancement.

The PLL freezing method was introduced in [207] and [208] to achieve a ZVRT capability with stable operation without needing current injection limits or additional control loops. However, that approach cannot address the phase jump. In [209], the PLL frequency-based method was used the detected frequency to regulate the active current reference to solve the loss of synchronization issue and enhance the transient stability, especially during very deep voltage sag. The adaptive current injection method was introduced in [210], which generates the post-fault equivalent grid impedance, and this was used to create the ratio of active and reactive current references by estimating the X/R ratio to enhance the system's dynamic performance, hence avoiding transient instability issues. The design-oriented analysis using the first-order PLL (FO-PLL) and the phase portrait for the transient stability was presented in [190]. This method increases the damping ratio to enable the VSC with SRF-PLL to operate in steady state operation that improves the transient stability and phase estimation accuracy in case of the fault occurring or cleaning. The transient stability enhancement methods are summarized in Table 8.

3) FREQUENCY SUPPORT ISSUES

The large frequency deviation, high ROCOF, and the coupling of RESs to the power grid using the fast-response power converter resulted in the lack of synthetic inertia [211], [212]. Many issues resulting from the lack of synthetic inertia, such as undesirable load shedding, cascading failure, and a large-scale blackout, are addressed and solved by emulating the virtual inertia (VI) using the DC-link capacitors [212].

TABLE 7. The summarized methods used for FRT enhancement.

Method	Improvements and advantages	Ref.
Hybrid grid synchronization (phase & frequency estimation using SO-SRF-PLL & arctangent methods)	• Simple and reliable. • The loss of synchronization duration is reduced. • Robust current controller dynamics are achieved.	[198]
SFCL & The resistive type of SFCL	• The generators and grid-side's fault currents are limited. • The DC-capacitor link overvoltage is reduced.	[199], [200]
BFCL controller	• The dynamics performance is enhanced. • The PMSG's speed and active power fluctuations are decreased. • The fault recovery process is accelerated.	[201]
Electrical spring with ANN controller	• The self-protective discontinuation of large-scale RESs is eliminated. • The LVRT capability is improved. • Act as voltage support in case of voltage sag.	[202]
A coordinated control method based variable ratio GB	• The mechanical power and rotor acceleration are reduced. • The system's efficiency and stability are enhanced.	[203]
A communication-free FRT	• The adverse impact of short circuit faults is effectively mitigated.	[204]
Two-stage conversion in on-grid PV system	• The stability and reliability are enhanced.	[205]
The EFOC technique with STATCOM used in DFIG-WT + dual SOGI-FLL	• The transient and dynamic stability are improved. • A correct active and reactive power are achieved.	[206]

TABLE 8. The summarized methods used for transient stability enhancement.

Method	Improvements and advantages	Ref.
PLL freezing method	• ZVRT capability and stable operation are achieved without needing current injection limits or additional control loops.	[207], [208]
PLL frequency-based method	• The transient stability is enhanced during very deep voltage sag.	[209]
The adaptive current injection method	• The system's dynamic performance is enhanced.	[210]
The design-oriented analysis based FO-PLL with phase portrait	• It operates in steady-state operation. • The transient stability is improved. • The phase estimation accuracy is improved.	[190]

This method effectively increases system inertia and reduces frequency deviations without increasing cost and complexity. The frequency variation is reduced by 12.5% using the approach in [212], hence the ROCOF could be improved up to 50%. To improve the grid stability frequency during the frequency disturbances in small-scale weak power grids, the distributed virtual inertia (DVI) regulator with a new current controller compensator was proposed to be integrated into the grid [213]. That acts as a primary frequency regulation. Also, maximum DVI support and a stable operation can be achieved in weak grid conditions using the approach in [213], while reducing the frequency nadir following the load disturbance and enhancing the ROCOF by 40.38%.

To reduce the output power fluctuation in the RESs, the virtual synchronous generator (VSG) was proposed to be integrated into the grid-connected converters. However, that is sensitive to the grid frequency disturbance. The work in [214] introduces the VI control without additional energy storage to solve such issue. A modified MAF-based FLL was used for frequency extraction in [214]. Using the VI control method based on PCC frequency feedforward improves the transient power performance. Also, the power oscillation is effectively suppressed, and the impact of power change on frequency performance is reduced. An enhanced frequency adaptive demodulation technique was introduced to eliminate the double frequency component with low computational complexity, fast convergence, and a good disturbance rejection in [215]. The synchronous active power control for the grid-connected converter was introduced in [216] to emulate a SGs for inertia characteristics and load sharing and provide the primary frequency control. The work in [217] introduced an enhanced control structure integrating the enhanced PLL (EPLL) state variables into the main converter controller. The bandwidth of the current controller, EPLL, filter parameters, and voltage feedforward path were designed to improve its performance in that work. The interaction between the EPLL and the main converter controller was minimized, showing a more robust performance and mitigating the grid voltage and frequency oscillations caused by the system instabilities over a wider range of weak and distorted grid conditions. The impact of energy storage system (ESS) response speed on enhanced frequency response (EFR) services was studied in [218]. It was concluded that the EFR performance is greatly dependent on communication latency. So, for better EFR performance, the communication latency must be reduced, resulting in increased power capacity. However, the wide integration of ESS is considered highly cost, low life, and low energy density. To solve this issue, the advanced ESS with utility inductors is introduced in [219]. Table 9 summarized methods used for frequency support enhancement. Also, Table 10 summarized all references used to enhance grid support issues.

VI. FUTURE CONSIDERATIONS

A. SELF-SYNCHRONIZED PLL

The conventional GFLs utilized PLLs for grid synchronization, extracting the estimated voltage phase, and frequency. The conventional GFLs have some limitations that appear in weak grid conditions, as mentioned above, such as voltage and frequency instability issues and side-band oscillations. One of the possible improvements is to be introduced using the PLL-less operation of GFLs based on direct power control (DPC). Instantaneous active and reactive power is used in the DPC method to control the power converter to achieve a good dynamics performance and to keep the unity power factor. The DPC structure does not have an inner current loop, resulting in limitations such as variable switching frequency and unexpected broadband harmonics spectrum range. Pulse width modulation (PWM) and space vector modulation (SVM) are used with the DPC method to avoid these limitations [220], [221], [222]. Model predictive control-based DPC methods (MPC-DPCs) are introduced to achieve constant switching frequency by considering all non-linearities and constraints on the system. However, compared with the DPC method, the MPC-DPCs result in a heavier computational burden [223], [224], [225].

Another PLL-less control method also available in the literature is a voltage-modulated DPC (VMDPC) method which is the same structure as the conventional vector current control methods [226], [227], [228], [229]. This method improves the steady-state performance, which is the main disadvantage of the DPC method. However, in weak conditions, that method suffers from instability problems because of its requirement for the reference voltage to control the power variation with the grid.

To avoid any need for voltage sensing or regulating, the new power-synchronized PLL-less control-based grid following converters (PSGFLI) was introduced in [230]. That method does not rely on PLL to synchronize with the grid like VMDPC. In addition, there is no need for PCC voltage regulation/sensing, and it is possible to operate in strong, weak, and ultra-weak grids. That method regulates the terminal power utilizing the vector current control in the inner loop and utilizes the outer loop for extraction of the grid frequency and generating the current references of its inner loop. It provides real and reactive power control and supports the protection capability by limiting the current injection to the grid. However, its dynamics performance depends on the selected bandwidth and the operating point, which means the complexity of the design parameter is increased. The work in [230] is extended to rectify the shortcomings of the PSGFLI utilizing a linear parameter varying (LPV) loop-shaping controller for PSGFLI called (LPV-PSGFLI) which is a straightforward control design based on the converter-based resources operating point [231], and it can work as a bidirectional converter. A constant bandwidth is used for different operating points using that structure, indicating the performance does not depend on the operating points. The works in [230] and [231] shows the effectiveness of that control method. However, a voltage drop across the converter's output filter would appear because of the measurements required at the converter terminal rather than the PCC [232].

The GFL converters inject specific active and reactive power to the grid according to the LVRT requirement. Unbalanced grid voltages can cause an uncontrollable oscillation resulting in an unbalanced current injection. Based on that, a double-synchronous-reference-frame (DSRF) based PSGFIs (DSRF-PSGFIs) was proposed in [233] to enable reliable operation in strong and weak grid conditions by mitigating instabilities resulting from the system strength variation, the system frequency deviation, and the unbalanced grid fault conditions.

In that approach, the outer loop regulates the PCC's positive active and reactive power and generates the positive phase angle required for the grid synchronization and the positive current references. The two inner loops are utilized independently to control the positive and negative sequences and to extract the current measurements. During the unbalanced grid faults, the negative sequence loop adjusts its output to mitigate the oscillations. This control method prevents voltage drops and high voltage harmonics from occurring at the converter terminals [234].

The enhanced PSGFLI (i.e., EPSGFLI) was proposed in [235] to address the issues faced by the PSGFLI and LPV-PSGFLI and to solve the instability resulting from the use of the conventional GFLIs. The loop-shaping design achieves a stable operation and accurate grid frequency estimation. It regulates converter terminal power by measuring output current, utilizing voltage reference, and eliminating a voltage sensor. The inner current loop is similar to the GFLI, while the outer power loop generates a frequency and the current reference. A fixed bandwidth of the power control loop can be used for any given operating point to ensure a stable operation in strong, weak, and ultra-weak grids.

The summarized comparison of the PLL-less power-synchronized control method regarding work principles, advantages, and disadvantages are illustrated in Table 11.

B. GRID FORMING TECHNOLOGY

The GFM converter, as its name implies, can form a local grid when the main grid is lost due to system disturbances or in the case of off-grid systems. That is why a PLL is necessary in the case of GFL converter and is not required in the case of GFM converter. This property is advantageous in distributed generation systems or in microgrids operating in the islanded mode. Besides, the GFM converter operation

TABLE 9. The summarized methods used for frequency support enhancement.

Method	Improvements and advantages	Ref.
Emulated VI using DC-link capacitors	• The system's inertia is increased. • The frequency deviation is reduced. • The ROCOF is improved. • The use of this method doesn't affect the design complexity and the cost.	[212]
A new current controller compensator integrated into the DVI regulator	• It achieved a maximum DVI support. • It enables a stable operation in weak grid conditions. • The frequency nadir is reduced. • The ROCOF is enhanced by 40.38%.	[213]
The modified VSG method with modified MAF-FLL	• The power oscillation is effectively suppressed. • The impact of power change on the frequency performance is reduced. • The transient power performance is improved.	[214]
An enhanced frequency adaptive demodulation technique	• A double-frequency component is eliminated. • Low computational complexity. • Fast convergence. • Good disturbance rejection.	[215]
Synchronous active power control	• It accurately supports the frequency. • Easy controller implementation.	[216]
Enhanced control structure EPLL integrated into the main converter controller	• The grid voltage and frequency oscillations over a wider range of weak and distorted grid conditions are effectively mitigated.	[217]
Advanced ESS with utility inductors	• The frequency fluctuation is effectively mitigated.	[219]

TABLE 10. The enhancement of the different grid support issues available in the literature.

Grid support issues enhancement	Refs.
FRT enhancement	[3], [172], [190], [195]-[206]
Transient stability enhancement	[190], [207]-[210]
Frequency support enhancement	[212]-[219]

is advantageous during system contingencies. The PLL is a source of stability issues and deteriorate the interaction between the power controller and the PLL itself as discussed in above and researchers tried to improve PLL related instabilities for GFL converters as discussed in Subsection V-B in details. The GFM converter is able to operate in autonomous mode and can be tuned and controlled efficiently to adjust the voltage and frequency forming a localized network. For that reason, it is constructed by a low impedance to an ideal AC voltage source. As the GFM converter was initially applied in microgrid systems, it could operate as a grid supporting converter in grid connected mode and can operate in islanded mode. This is considered as another advantage of the GFM converter over the GFL converter which always needs the main grid as a reference. The GFM converter is represented in practice as a standby uninterruptable power supply which can form a local grid when the main grid is disconnected [236].

In a GFL converter, the injected current is regulated with a specific phase displacement from the voltage of the grid at the point of common coupling. In this case, the fundamental frequency of the voltage phasor is needed all the time to correctly calculate the current reference in which the grid voltage amplitude and angle are precisely modified by control loops to deliver the required amount of real and reactive power [237].

In a GFM converter, the voltage magnitude and phase are regulated at the point of common coupling. Therefore, the recognition of the grid fundamental voltage and frequency is not that important. Here the network characteristics to which the converter is connected, and the proper control unit forms an isolated system. Thus, the instantaneous real and reactive power can be adapted by additional outer control loops [238].

In comparison to the GFL converter, the GFM converter has the following features [239]:

- It can form itself the voltage and frequency in case of off-grid system.
- It can operate in synchronization with the main utility grid in case of grid connected mode (as a grid supporting converter).
- It can detect islands and grid connected operation.
- It can remain connected during transient conditions when equipped with adequate current limiting methodology.

On the other hand, the control strategies of the GFM converter which employs PLL-free controls can be classified as the following:

- Droop control
- Virtual synchronous machine
- Virtual oscillator controllers

The methods shown above have similar properties despite the variation of each method. However, the output of the abovementioned GFM controllers change when the power of

TABLE 11. The summarized comparison of the PLL-less power-synchronized control method regarding work principles, advantages, and disadvantages.

PLL-less Power-synchronized control method	The comparison	
PSGFLI	Working principle	It regulates the terminal power using two control loops: • The inner loop utilizing vector current control. • The outer loop extracts the grid frequency and generates current references to its inner loop.
	Advantages	• No need for voltage regulating or sensing. • It operates in strong, weak, and ultra-weak grids. • It supports the protection capability. • It provides decoupling active and reactive power
	Disadvantages	• Its performance depends on the selected operating point. • The optimization-based tuning of the outer power loop is complex.
LPV-PSGFI	Working principle	It regulates the terminal active and reactive power using LPV loop-shaping controller.
	Advantages	• The control design method is straightforward. • It works as a bidirectional converter.
	Disadvantages	• It resulted in a voltage drop across the converter output filter, mainly when the high-power converter is used. • It suffers from steady-state errors and instability during the frequency deviations.
DSRF-PSGFI	Working principle	It regulates the power at the PCC using the following: • The outer loop regulates the PCC's positive active and reactive power and generates the positive phase angle required for the grid synchronization and the positive current references. • Two inner loops are utilized independently to control the positive and negative sequences and to extract the current measurements.
	Advantages	• It is reliable to operate in strong and weak grids effectively. • It prevents voltage drops and high voltage harmonics from occurring at the converter terminals. • It handles frequency deviations and unbalanced fault conditions.
	Disadvantages	×
EPSGFLI	Working principle	It regulates converter terminal power by measuring output current, utilizing voltage reference, and eliminating a voltage sensor using the following: • The inner current loop is similar to the GFL • The outer power loop generates a frequency and the current reference.
	Advantages	• The active and reactive power loops are effectively decoupled. • The power and grid frequency is accurately tracked. • It is stable under large frequency deviation without any steady-state errors.
	Disadvantages	×

the GFM converter, or the load demand are varied. In this way, the GFM converter instantaneously satisfies the load demand with the generated output power, regulate the voltage and the frequency itself [12].

Despite the massive research on the GFM converter, some future paths still need more investigations like:

- The applicability of the GFM converter into the transmission network.
- The hardware implementation of the GFM converter including energy storage.
- The needed protection and FRT capability.
- The economic aspects and economic dispatching of units.
- The transition from islanded mode to grid connected mode.

The increasing rate of using converter-based systems and the vastness of renewables into the network brings many challenges into the power grid performance. Several issues regarding the stability, continuity of the power supply, and system protection have been put forward [49], [240], [241]. Although the GFL converters are already wide and common type of converter based renewables, the GFM converter has testified huge commitment in maintaining stable operation of the power grid dominating renewables [242].

However, as this technology is still at its early stage, the modeling and control approaches in addition to their application still need more investigations by reviewing the relevant literature. In [243] and [244], different control methods of virtual synchronous generator are discussed. The difficulties and potential for improvement in addition to the application in grid frequency support have also been investigated. In [245], the GFM converter including estimation problems and virtual inertia modeling are discussed. In [246], the GFM converter difficulties including the FRT capability, the transition between grid connected mode and islanded mode, synchronization stability and limiting methods are discussed.

In the context of microgrids, the load unbalance presence of one of the three phases will cause system voltage unbalance. Thus, the GFM voltage balancing capability should be evaluated during the existence of such load unbalance. This is determined by the knowledge of the voltage source capacity in providing negative and zero sequence currents when an unbalance load is present. In [247], the range of sequence current to which the GFM converters can provide in an unbalanced system is identified despite the fact that required amount of zero and negative sequence currents are not estimated for a given unbalanced load. In [248], the voltage at the point of interconnection is balanced through a unified control strategy irrespective of the microgrid operation mode. However, there is a lack knowledge on how the voltage balancing is done for both operation modes either islanded or grid-connected. In [249], a four-leg GFM converter incorporating a multiple loop control strategy operating with unbalanced load is proposed. However, the criterion for needed adjustment to achieve voltage balancing is not specified well.

In islanded systems, the GFM converter plays a significant role in regulating the voltage and frequency of the system similar to the synchronous generator in grid connected systems. Accordingly, it is important to investigate how these GFM converters act during fault conditions. The fault behavior of GFM converters during unbalanced faults has attracted little concentration in the recent literature. In [250] and [251], the fault behavior of the GFM converter has been investigated through simulations and experiments.

During grid disturbances, the GFM converter compared to the SGs is susceptible to the variation in grid voltage due to the low short circuit capacity. Although converters in general may be tripped to avoid damage due to large current transients, the GFM converter have to remain grid-connected and ride through grid faults in future renewable dominated power systems [252]. Furthermore, the transient stability should be taken into consideration by employing a current limiting approach of the GFM converter where some of the current limiting methods of the GFM converter are discussed in [251] and [253].

VII. CONCLUSION

The integration of renewable energy sources (RESs) is a global priority for energy sector decision-makers. However, challenges are posed when transitioning from conventional systems with synchronous generators (SGs) to systems with a high RESs share, as system support functions such as voltage and frequency control are reduced with the decommissioning of SG-based central generation units. Although efforts have been made to compensate for SGs using current converter technologies, they remain heavily reliant on SG presence, hindering RESs integration as penetration increases. Thus, it is crucial to reevaluate grid-following (GFL) converters, their control mechanisms, and grid codes to understand their limitations and advancements.

In this paper, the concepts of low inertia systems and weak grids are presented. The issues and challenges of operation of power systems with high penetration of RESs under such low inertia and weak grids are discussed in more detail. This paper has also provided an overview about the control of GFL converters which are commonly used for interfacing the RESs. The GFL structure and the basic control methods are studied. Since the PLL is the heart of the GFL and is used in grid synchronization, different PLLs available in the literature are revised in terms of advantages, disadvantages, and the type of disturbances able to reject, such as double frequency oscillation, DC offset, and the harmonics. The grid code requirements for connecting RESs in different countries are reviewed to ensure reliable and stable grid performance. In addition, the operation of such GFL converters in weak grid conditions is also discussed in terms of challenges and mitigating solutions. This covers a wide range of functionalities and supporting means such as: voltage/frequency stability, the PLL's synchronization, and the grid support functionalities.

Different control ancillary services and the advancements concerning grid-support and droop control functions are summarized in terms of the objective and the drawbacks. Finally, the future considerations and the possible improvement are stated focusing on; the enhanced the GFL functionality and self-synchronized PLL.

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