Flexible Current Control Strategies Applied to LVRT Capability

Subjects: Engineering, Electrical & Electronic

Contributor: David J. Rincon , Maria A. Mantilla , Juan M. Rey , Miguel Garnica , David Javier Rincon , Damien Guilbert

Distributed power generation plays a critical role in the stability and reliability of modern power systems. Due to the rapid growth of renewable energy generation, the requirements of the transmission and distribution system operators are becoming more stringent. Among these requirements, one of the most important is the Low-Voltage Ride-Through (LVRT) capability, which demands that the inverters remain connected to the grid and provide support during voltage sags. For this purpose, flexible current control algorithms stand out because they can manage unbalanced voltages and simultaneously achieve other control objectives.

flexible current control | LVRT | voltage support

1. Introduction

Over the last decade, there has been a growing penetration of renewable generation systems into the grid due to environmental factors and the decrease in their costs [1][2][3]. These systems include photovoltaic arrays, wind turbines, and fuel cells, among others. However, the large integration of distributed power generation systems (DPGS) can have a negative impact on the stability and reliability of power systems [4][5][6]. As a result, several countries have upgraded their grid codes (GCs) to regulate the interconnection of DPGS to the grid [7][8][9][10]. A critical GC requirement is the Low-Voltage Ride-Through (LVRT) capability, which states that the DPGS shall remain connected to the grid during a voltage sag to avoid sudden tripping and loss of power generation [11][12][13][14]. In this sense, voltage support is the main goal of the LVRT capability [15]. The aim is to recover the voltage level as much and as quickly as possible.

For a suitable LVRT control action, general criteria establish that the sag has to be quickly detected, and the full power capacity of the inverter must be exploited [16][17]. In addition, three variables are considered critical for the safety of the inverter: (1) maximum AC output current, (2) maximum AC output voltage, and (3) maximum DC-link voltage [18]. Therefore, the voltage support must be performed, limiting these parameters to safe operation points. Furthermore, grid codes requirements such as the minimum value of injected currents and the maximum voltage level at the Point of Common Coupling (PCC) must be considered. Other secondary objectives, such as minimizing voltage oscillations on the DC-link and reducing harmonic content on the injected currents, are also desirable. Among the alternatives of control strategies to execute voltage support, flexible current control algorithms have drawn attention for their capacity to achieve more than one control objective simultaneously [19][20][21][22]. Based on the *p-q* power theory, flexible current control algorithms decompose unbalanced fault voltages in symmetric sequences on the αβ0 frame, allowing the regulation of the amount of active and reactive powers injected through the positive and negative sequences [23].

Many proposals of flexible control have been presented, which are characterized by improving operational performance using more complex control strategies. In the specialized literature, some papers as [24][25] present reviews of control techniques under different grid faults scenarios. However, considering that these works present a broad view of this application, the discussion of the specific characteristics and potentials of flexible control for LVRT operation is very limited.

2. LVRT Considerations

The growth in the penetration of grid-connected DPGS has led to changes in the ancillary services required by the GCs in order to guarantee the stability and reliability of distribution systems. To better understand the operation of DPGS during grid faults, this section presents the main aspects of voltage sags, reviews LVRT requirements in different GCs, and discusses some common strategies for voltage support.

2.1. Voltage Sags

A voltage sag is a short-time reduction in the RMS voltage value of one or more grid phases. They can be caused by short circuits, overloads, and the starting of large motors. Table 2 of IEEE Std 1159 categorizes different electromagnetic phenomena, including voltage sags [26]. According to this standard, the magnitude of typical voltage sags is between 0.1 and 0.9 Vpu. Nevertheless, some grid codes consider LVRT profiles from 0 to 0.9 Vpu (e.g., the German code). Although magnitude and duration are the main characteristics of voltage sags, other features such as phase angle jumps and unbalance must be considered . In fact, the occurrence of symmetrical faults is rare (close to 2–3% overall). Therefore, most grid faults are asymmetrical, generating negative and zero sequence voltages in the network .

2.2. Grid Code Requirements

GCs are a collection of technical specifications to coordinate the operation and integration of different power generators to the grid. They are imposed by the transmission and distribution system operators seeking to guarantee the stability and regulation of the system frequency and voltage [31][32]. Over the last decade, the DPGS requirements have become more stringent in many countries due to the considerable rise in renewable energy generation [33]. In this sense, GCs usually require the DPGS to stay connected to the grid during voltage sags. Moreover, maximum current and reactive current injection (RCI) are requested in order to support the voltage recovery. Once the fault is cleared, the DPGSs must resume active power supply [34]. A voltage vs. fault duration profile is defined to consider the safety of the equipment.

In the same way, some GCs define a minimum RCI profile to provide voltage support [35][36]. However, this requirement is based on the assumption that grid impedance is mainly inductive, which is not always valid (e.g., low-voltage microgrids have a mainly resistive impedance). In fact, many authors have found that the grid impedance must be taken into account to optimize the voltage support [37][38][39]. Another feature to mention is that some GCs determine the RCI requirement considering the on-grid voltage reduction during the fault and the nominal power and current of the source, e.g., GCs of Germany and Colombia [40][41].

2.3. Voltage Support Strategies and Secondary Objectives

Modern GCs must be adapted to overcome the challenge that the massive integration of renewable energies will pose to the power quality of electrical systems [42]. For instance, the suitable characterization of the grid impedance Zg and the voltage support strategy selection play a relevant role in the voltage recovery. Camacho et al. has proposed three basic approaches of voltage support strategies: the first is an approach in which the positive sequence voltage support is maximized [39]. In this case, all the phase voltages are raised equally by injecting active and reactive power only through the positive sequence. However, unfaulted phases can present a troublesome over-voltage due to the unbalance [43]. The second is an approach in which the negative sequence voltage is minimized to reduce the unbalance between phases. Therefore, it is necessary to consume active power through the negative sequence, which is the major inconvenience of this strategy since a backup (EES) or an element to dissipate the power is required. The third is an approach that combines the two mentioned methods, and its goal is to maximize the difference between the positive and negative sequence voltages. According to Camacho et al., this strategy is the most convenient to restore the voltages to the values prior to the occurrence of the fault [39]. Other control proposals have focused on maximizing the power delivered and the injection of currents, which result in a non-controlled voltage support [19][21][42].

In addition to the voltage support, other LVRT secondary objectives such as minimizing the DC-link voltage oscillations, reducing harmonic components on injected currents, and mitigating power oscillations are also desired [44][45][46][47][48]. To improve the inverter performance, achieving these secondary objectives is not a simple task, since the three main system restrictions must be considered: (1) maximum phase current limit, (2) maximum phase voltage limit, and (3) maximum DC-link voltage limit [18]. In addition, there are regulatory restrictions such as the minimum amount of injected current, LVRT voltage profiles, and the maximum phase voltage allowed by the GC [42][43]. Furthermore, the LVRT control strategy should also consider the type and severity of the fault, the grid characteristics, and the power generation and power curtailment scenarios. For these reasons, it is a common practice to organize the secondary objectives in a hierarchical control structure [34].

3. System Description

3.1. Grid-Connected Inverter

The DC stage comprises the power source (renewable generation or storage systems). An optional DC-DC converter is mainly used to manage the voltage level and control the generated power [49]. A DC-link capacitor Cdc is used to balance the power exchange between the inverter and the DC-stage. A filter is implemented at the output of the three-phase inverter to reduce the high-frequency harmonics [50][51]. The grid effect is usually modeled with a line impedance Zg and a voltage source Vg. Although not included in the scheme, some loads could be connected at the PCC, and Zg may include the impedance of a power transformer between the inverter and the grid.

3.2. Control Loops

Briefly, during fault conditions, the reference current must be calculated to improve the voltage support while complying with the system restrictions. The synchronization algorithm estimates the grid frequency ω and the symmetric components of the PCC voltages [52][53][54][55]. The current controller tracks the reference signal and generates the pulses for the inverter [56][57]. The generation control manages the power production at the renewable source.

According to the general criteria of the specialized literature, employing the full inverter capacity and a fast response are desired. It can be established that the synchronization algorithm and the current controller are mainly related to the reaction time of the inverter. One is responsible for sensing and obtaining the information of the PCC fault voltages, and the other implements the control's actions through the inverter switching. On the other hand, generation control and reference current algorithms are responsible for exploiting the inverter's full capacity.

4. Flexible Current Control Algorithms

Flexible current algorithms are selected for the calculation of current reference signals during voltage sags, since these allow the injection of different amounts of active and reactive powers via positive and negative sequences [21]. Moreover, the flexible approach allows the manipulation of the power loops to avoid distorted currents and cancel power oscillations as well as other operational features.

4.1. Basic Formulation

First, some basic definitions are presented in order to state some principles of the flexible current control. For this strategy, the PCC voltages are decomposed in symmetric sequences on the αβ0 frame, as shown in (1), where V+, V−, φ+, and φ− are the amplitudes and phases of the positive- and negative-sequences voltages and ω is the grid angular frequency [23][34]. Moreover, the instantaneous active power *p* and the instantaneous reactive power *q* are defined by (2) according to the *p*-*q* theory [58][59].

$$\begin{aligned} v_\alpha &= v_\alpha^+ + v_\alpha^- = V^+ cos\left(\omega t + \varphi^+\right) + V^- cos\left(\omega t + \varphi^-\right) \\ v_\beta &= v_\beta^+ + v_\beta^- = V^+ sin\left(\omega t + \varphi^+\right) - V^- sin\left(\omega t + \varphi^-\right) \end{aligned} \quad (1)$$

$$p = \frac{3}{2}(v_\alpha i_\alpha + v_\beta i_\beta)$$
$$q = \frac{3}{2}(v_\beta i_\alpha + v_\alpha i_\beta) \quad (2)$$

Using (1) and (2), the reference currents i∗α and i∗β can be expressed in terms of the reference powers P∗ and Q∗, as shown in (3). Notice that the currents have a cosine term in the denominator that only appears if the PCC voltage is composed of positive and negative sequences.

$$i_\alpha^* = \frac{2}{3}\frac{(v_\alpha^+ + v_\alpha^-)P^* + \left(v_\beta^+ + v_\beta^-\right)Q^*}{(V^+)^2 + (V^-)^2 + 2V^+V^-cos(2\omega t + \varphi^+ + \varphi^-)}$$
$$i_\beta^* = \frac{2}{3}\frac{\left(v_\beta^+ + v_\beta^-\right)P^* - (v_\alpha^+ + v_\alpha^-)Q^*}{(V^+)^2 + (V^-)^2 + 2V^+V^-cos(2\omega t + \varphi^+ + \varphi^-)} \quad (3)$$

Similar expressions can be obtained on the dq0 frame [60][61]. However, working in the dq0 frame under unbalanced conditions does not bring additional benefits beyond those obtained by working in the αβ0 frame, since the respective voltage components have a sinusoidal behavior in both cases [59].

4.2. Fundamental Concepts of Flexible Control

The main characteristic of a flexible strategy is the ability to modify the control algorithm using scalar factors to achieve the desired control characteristics. The foundations of flexible control are presented by Rodriguez [20] in the following control strategies:

- Instantaneous Active Reactive Control (IARC);
- Instantaneously Controlled Positive-Sequence (ICPS);
- Positive-Negative-Sequence Compensation (PNSC);
- Average Active-Reactive Control (AARC);
- Balanced Positive-Sequence Control (BPSC).

The first formal introduction of the concept *flexible* for current control in three-phase inverters corresponds to a variation of the PNSC strategy called Flexible Positive- and Negative-Sequence Control (FPNSC) proposed by the same Rodriguez et al. [60]. Equation (4) presents the reference currents for the PNSC strategy, where v+ is the positive sequence voltage vector and v+⊥ is an orthogonal version of v+, led 90∘ by the original vector [62]. The same definition can be applied to v− and v−⊥ considering the negative sequence instead of the positive one. Therefore, the voltage vector v can be expressed as v=v++v− (refer to Teodorescu et al. [60] and Mehmet et al. [61] for a detailed explanation).

$$\mathbf{i}_p^* = \frac{P^*}{|\,\boldsymbol{v}^+\,|^2 - |\,\boldsymbol{v}^-\,|^2}(\boldsymbol{v}^+ - \boldsymbol{v}^-)$$
$$\mathbf{i}_q^* = \frac{Q^*}{|\,\boldsymbol{v}^+\,|^2 - |\,\boldsymbol{v}^-\,|^2}(\boldsymbol{v}_\perp^+ - \boldsymbol{v}_\perp^-) \quad (4)$$

Equation (5) shows the reference currents according to the FPNSC. The most important remark is the introduction of the scalar factors k1 and k2, which explains why the FPNSC is considered a flexible control. Constants k1 and k2 are used to regulate the amount of active and reactive power injected through the positive and the negative sequences.

$$\begin{aligned} \mathbf{i}_p^* &= k_1 \frac{P^*}{|\boldsymbol{v}^+|^2}\boldsymbol{v}^+ + (1-k_1)\frac{P^*}{|\boldsymbol{v}^-|^2}\boldsymbol{v}^- \\ \mathbf{i}_q^* &= k_2 \frac{Q^*}{|\boldsymbol{v}^+|^2}\boldsymbol{v}_\perp^+ + (1-k_2)\frac{Q^*}{|\boldsymbol{v}^-|^2}\boldsymbol{v}_\perp^- \end{aligned} \tag{5}$$

Notice that for the particular case in which k1=k2=|v+|2/(|v+|2−|v−|2), (5) will be equal to (4), so PNSC corresponds to a specific design case of FPNSC. Although in some cases, the scalar factors kihave a physical meaning, these are usually implemented as a control variable that allows accomplishing specific objectives during voltage sags. For this reason, any flexible current formulation usually has multiple variations. For example, (6) shows an FPNSC control variation proposed by Mehmet et al. [61]. In this case, the objective is to mitigate the active and reactive powers' oscillating components. Therefore, Mehmet et al. have proposed only one scalar factor that is applied to the negative sequence voltage components [61].

$$\begin{aligned} \mathbf{i}_p^* &= \frac{P^*}{|\boldsymbol{v}^+|^2 + k|\boldsymbol{v}^-|^2}\left(\boldsymbol{v}^+ + k\boldsymbol{v}^-\right) \\ \mathbf{i}_q^* &= \frac{Q^*}{|\boldsymbol{v}^+|^2 + k|\boldsymbol{v}^-|^2}\left(\boldsymbol{v}_\perp^+ + k\boldsymbol{v}_\perp^-\right) \end{aligned} \tag{6}$$

Another typical characteristic of flexible current algorithms is the possibility of avoiding distorted currents. This can lead to the appearance of an oscillating component in the injected powers. This approach is used in the AARC strategy of Rodriguez et al. [20], where the RMS value of the grid voltages is used instead of the instantaneous values.

$$\begin{aligned} i_\alpha^* &= \frac{2}{3}\frac{\left(v_\alpha^+ + v_\alpha^-\right)k\,P^* + \left(v_\beta^+ + v_\beta^-\right)k\,Q^*}{\left(V^+\right)^2 + \left(V^-\right)^2} \\ i_\beta^* &= \frac{2}{3}\frac{\left(v_\beta^+ + v_\beta^-\right)k\,P^* - \left(v_\alpha^+ + v_\alpha^-\right)k\,Q^*}{\left(V^+\right)^2 + \left(V^-\right)^2} \end{aligned} \tag{7}$$

This expression corresponds to a general formulation. Indeed, if *k* is selected according to (8), the specific design case in (3) is obtained.

$$k = \frac{\left(V^+\right)^2 + \left(V^-\right)^2}{\left(V^+\right)^2 + \left(V^-\right)^2 + 2V^+V^-cos\left(2\omega t + \varphi^+ + \varphi^-\right)} \tag{8}$$

Thus, the flexible approach allows setting the value of *k* to achieve desired control characteristics, including the removal of the term on the denominator in (3). To determine the appropriate values of *k*, the injected powers are calculated by replacing (7) into (2).

$$p = \left(1 + \frac{2V^{+}V^{-}cos\left(2\omega t + \varphi^{+} + \varphi^{-}\right)}{\left(V^{+}\right)^{2} + \left(V^{-}\right)^{2}}\right) k\, P^{*}$$
$$q = \left(1 + \frac{2V^{+}V^{-}cos\left(2\omega t + \varphi^{+} + \varphi^{-}\right)}{\left(V^{+}\right)^{2} + \left(V^{-}\right)^{2}}\right) k\, Q^{*} \quad (9)$$

References

1. Blaabjerg, F.; Yang, Y.; Yang, D.; Wang, X. Distributed Power-Generation Systems and Protection. Proc. IEEE 2017, 105, 1311–1331.
2. Ufa, R.; Malkova, Y.; Rudnik, V.; Andreev, M.; Borisov, V. A review on distributed generation impacts on electric power system. Int. J. Hydrogen Energy 2022, 47, 20347–20361.
3. Chen, X.; Mcelroy, M.B.; Wu, Q.; Shu, Y.; Xue, Y. Transition towards higher penetration of renewables: An overview of interlinked technical, environmental and socio-economic challenges. J. Mod. Power Syst. Clean Energy 2019, 7, 1–8.
4. Kundur, P.; Paserba, J.; Vitet, S. Overview on definition and classification of power system stability. In Proceedings of the CIGRE/IEEE PES International Symposium Quality and Security of Electric Power Delivery Systems. CIGRE/PES 2003, Montreal, QC, Canada, 8–10 October 2003; pp. 1–4.
5. Peyghami, S.; Palensky, P.; Blaabjerg, F. An Overview on the Reliability of Modern Power Electronic Based Power Systems. IEEE Open J. Power Electron. 2020, 1, 34–50.
6. Tse, C.K.; Huang, M.; Zhang, X.; Liu, D.; Li, X.L. Circuits and Systems Issues in Power Electronics Penetrated Power Grid. IEEE Open J. Circuits Syst. 2020, 1, 140–156.
7. Zeb, K.; Islam, S.U.; Khan, I.; Uddin, W.; Ishfaq, M.; Curi Busarello, T.D.; Muyeen, S.; Ahmad, I.; Kim, H. Faults and Fault Ride Through strategies for grid-connected photovoltaic system: A comprehensive review. Renew. Sustain. Energy Rev. 2022, 158, 112125.
8. Zhang, Z.; Schuerhuber, R.; Fickert, L.; Friedl, K. Study of stability after low voltage ride-through caused by phase-locked loop of grid-side converter. Int. J. Electr. Power Energy Syst. 2021, 129, 106765.
9. Özgür, Ç.; Yalman, Y.; Tan, A.; Çağatay Bayındır, K.; Ümit, Ç.; Akdeniz, M.; Chaudhary, S.K.; Høyer, M.; Guerrero, J.M. Grid code requirements—A case study on the assessment for integration of offshore wind power plants in Turkey. Sustain. Energy Technol. Assessments 2022, 52, 102137.
10. Heydari-doostabad, H.; Khalghani, M.R.; Khooban, M.H. A novel control system design to improve LVRT capability of fixed speed wind turbines using STATCOM in presence of voltage fault. Int. J. Electr. Power Energy Syst. 2016, 77, 280–286.
11. Howlader, A.M.; Senjyu, T. A comprehensive review of low voltage ride through capability strategies for the wind energy conversion systems. Renew. Sustain. Energy Rev. 2016, 56, 643–658.
12. Tang, C.Y.; Chen, Y.T.; Chen, Y.M. PV Power System With Multi-Mode Operation and Low-Voltage Ride-Through Capability. IEEE Trans. Ind. Electron. 2015, 62, 7524–7533.
13. Benali, A.; Khiat, M.; Allaoui, T.; Denaï, M. Power Quality Improvement and Low Voltage Ride Through Capability in Hybrid Wind-PV Farms Grid-Connected Using Dynamic Voltage Restorer. IEEE Access 2018, 6, 68634–68648.

14. Guo, X.; Liu, W.; Lu, Z. Flexible Power Regulation and Current-Limited Control of the Grid-Connected Inverter Under Unbalanced Grid Voltage Faults. IEEE Trans. Ind. Electron. 2017, 64, 7425–7432.

15. Al-Shetwi, A.Q.; Hannan, M.; Jern, K.P.; Mansur, M.; Mahlia, T. Grid-connected renewable energy sources: Review of the recent integration requirements and control methods. J. Clean. Prod. 2020, 253, 119831.

16. Al-Shetwi, A.Q.; Sujod, M.Z.; Blaabjerg, F.; Yang, Y. Fault ride-through control of grid-connected photovoltaic power plants: A review. Sol. Energy 2019, 180, 340–350.

17. Talha, M.; Amir, A.; Raihan, S.R.S.; Abd Rahim, N. Grid-connected photovoltaic inverters with low-voltage ride through for a residential-scale system: A review. Int. Trans. Electr. Energy Syst. 2021, 31, e12630.

18. Milicua, A.; Abad, G.; Rodríguez Vidal, M.A. Online Reference Limitation Method of Shunt-Connected Converters to the Grid to Avoid Exceeding Voltage and Current Limits Under Unbalanced Operatio—Part I: Theory. IEEE Trans. Energy Convers. 2015, 30, 852–863.

19. Sosa, J.L.; Castilla, M.; Miret, J.; Matas, J.; Al-Turki, Y.A. Control Strategy to Maximize the Power Capability of PV Three-Phase Inverters During Voltage Sags. IEEE Trans. Power Electron. 2016, 31, 3314–3323.

20. Rodriguez, P.; Timbus, A.V.; Teodorescu, R.; Liserre, M.; Blaabjerg, F. Flexible Active Power Control of Distributed Power Generation Systems During Grid Faults. IEEE Trans. Ind. Electron. 2007, 54, 2583–2592.

21. Camacho, A.; Castilla, M.; Miret, J.; Borrell, A.; de Vicuña, L.G. Active and Reactive Power Strategies With Peak Current Limitation for Distributed Generation Inverters During Unbalanced Grid Faults. IEEE Trans. Power Electron. 2015, 62, 1515–1525.

22. Afshari, E.; Moradi, G.R.; Rahimi, R.; Farhangi, B.; Yang, Y.; Blaabjerg, F.; Farhangi, S. Control Strategy for Three-Phase Grid-Connected PV Inverters Enabling Current Limitation Under Unbalanced Faults. IEEE Trans. Ind. Electron. 2017, 64, 8908–8918.

23. Camacho, A.; Castilla, M.; Miret, J.; Vasquez, J.C.; Alarcon-Gallo, E. Flexible Voltage Support Control for Three-Phase Distributed Generation Inverters Under Grid Fault. IEEE Trans. Ind. Electron. 2013, 60, 1429–1441.

24. Jia, J.; Yang, G.; Nielsen, A.H. A Review on Grid-Connected Converter Control for Short-Circuit Power Provision Under Grid Unbalanced Faults. IEEE Trans. Power Del. 2018, 33, 649–661.

25. Joshi, J.; Swami, A.K.; Jately, V.; Azzopardi, B. A Comprehensive Review of Control Strategies to Overcome Challenges During LVRT in PV Systems. IEEE Access 2021, 9, 121804–121834.

26. IEEE Std 1159-2019 (Revision of IEEE Std 1159-2009); IEEE Recommended Practice for Monitoring Electric Power Quality. IEEE: Piscataway, NJ, USA, 2019; pp. 1–98.

27. Bollen, M.H. Understanding Power Quality Problems: Voltage Sags and Interruptions; John Wiley& Sons, Inc: Hoboken, NJ, USA, 2000; pp. 139–251.

28. Garnica, M.; García de Vicuña, L.; Miret, J.; Camacho, A.; Guzmán, R. Voltage Support Experimental Analysis of a Low-Voltage Ride-Through Strategy Applied to Grid-Connected Distributed Inverters. Energies 2018, 11, 1949.

29. Swagata Das, S.S.; Ananthan, S.N. Fault Location on Transmission and Distribution Lines: Principles and Applications; John Wiley & Sons: Hoboken, NJ, USA, 2022; p. 2.

30. Tleis, N. Power Systems Modelling and Fault Analysis; Academic Press: Cambridge, MA, USA, 2022; p. 12.

31. Tarafdar Hagh, M.; Khalili, T. A review of fault ride through of PV and wind renewable energies in grid codes. Int. J. Energy Res. 2019, 43, 1342–1356.

32. Yadav, M.; Pal, N.; Saini, D.K. Low voltage ride through capability for resilient electrical distribution system integrated with renewable energy resources. Energy Rep. 2023, 9, 833–858.
33. Buraimoh, E.; Davidson, I.E. Overview of Fault Ride-Through Requirements for Photovoltaic Grid Integration, Design and Grid Code Compliance. In Proceedings of the 2020 9th International Conference on Renewable Energy Research and Application (ICRERA), Glasgow, UK, 27–30 September 2020; pp. 332–336.
34. Garnica López, M.A.; García de Vicuña, J.L.; Miret, J.; Castilla, M.; Guzmán, R. Control Strategy for Grid-Connected Three-Phase Inverters During Voltage Sags to Meet Grid Codes and to Maximize Power Delivery Capability. IEEE Trans. Power Electron. 2018, 33, 9360–9374.
35. Zheng, Q.; Li, J.; Ai, X.; Wen, J.; Fang, J. Overview of grid codes for photovoltaic integration. In Proceedings of the 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China, 26–28 November 2017; pp. 1–6.
36. Sarkar, M.N.I.; Meegahapola, L.G.; Datta, M. Reactive Power Management in Renewable Rich Power Grids: A Review of Grid-Codes, Renewable Generators, Support Devices, Control Strategies and Optimization Algorithms. IEEE Access 2018, 6, 41458–41489.
37. Camacho, A.; Castilla, M.; Miret, J.; de Vicuña, L.G.; Miguel Andrés, G.L. Control Strategy for Distribution Generation Inverters to Maximize the Voltage Support in the Lowest Phase During Voltage Sags. IEEE Trans. Power Electron. 2018, 65, 2346–2355.
38. Celik, D.; Meral, M.E. Voltage Support Control Strategy of Grid-connected Inverter System Under Unbalanced Grid Faults to Meet Fault Ride Through Requirements. IET Gener. Transm. Distrib. 2020, 14, 3198–3210.
39. Camacho, A.; Castilla, M.; Miret, J.; de Vicuña, L.G.; Guzman, R. Positive and Negative Sequence Control Strategies to Maximize the Voltage Support in Resistive-Inductive Grids During Grid Faults. IEEE Trans. Power Electron. 2018, 33, 5362–5373.
40. Duong, M.Q.; Leva, S.; Mussetta, M.; Le, K.H. A Comparative Study on Controllers for Improving Transient Stability of DFIG Wind Turbines During Large Disturbances. Energies 2018, 11, 480.
41. Resolucion No 60 del 2019: Modificaciones al Reglamento de Operación para permitir la conexión y operación de plantas solares fotovoltaicas y eólicas en el SIN. Comisión de Regulación de Energía y Gas CREG. 2019. Available online: http://apolo.creg.gov.co/Publicac.nsf/1c09d18d2d5ffb5b05256eee00709c02/ca640edbe4b7b5100525842d0053745d/$FILE 2019.pdf (accessed on 27 December 2022).
42. Ge, J.; Shuai, Z.; Tu, C.; Luo, A.; Shen, Z.J. Flexible Control Strategy for Enhancing Power Injection Capability of Three-Phase Four-Wire Inverter During Asymmetrical Grid Faults. IEEE Trans. Power Electron. 2021, 36, 9592–9608.
43. Miret, J.; Garnica López, M.; Vicuña, L.; Camacho, A. PI-based controller for low-power distributed inverters to maximize reactive current injection while avoiding over voltage during voltage sags. IET Power Electron. 2018, 12, 83–91.
44. Shabestary, M.M.; Mohamed, Y.A.I. Advanced Voltage Support and Active Power Flow Control in Grid-Connected Converters Under Unbalanced Conditions. IEEE Trans. Power Electron. 2018, 33, 1855–1864.
45. Tafti, H.D.; Maswood, A.I.; Konstantinou, G.; Pou, J.; Townsend, C.D. Low-voltage ride-through capability of full-row connected cascaded H-bridge converters. In Proceedings of the 2016 IEEE Region 10 Conference (TENCON), Singapore, 22–25 November 2016; pp. 984–987.
46. Afshari, E.; Moradi, G.R.; Yang, Y.; Farhangi, B.; Farhangi, S. A review on current reference calculation of three-phase grid-connected PV converters under grid faults. In Proceedings of the 2017 IEEE Power and

Energy Conference at Illinois (PECI), Champaign, IL, USA, 23–24 February 2017; pp. 1–7.

47. Xu, C.; Xuehua, W.; Xinbo, R.; Cheng, W.; Huanyu, W. A Low-Voltage Ride-Through Control Strategy for Two-Stage T-Type Three-Level Photovoltaic Inverters Limiting DC-Link Overvoltage and Grid-Side Overcurrent. In Proceedings of the 2018 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe), Riga, Latvia, 17–21 September 2018; pp. P.1–P.10.
48. Naresh, P.; Sravan Kumar, V.S. Analysis of Low Voltage Ride Through Techniques for Grid-Connected Photovoltaic Systems. In Proceedings of the 2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE2020), Cochin, India, 2–4 January 2020; pp. 1–7.
49. Mahela, O.P.; Shaik, A.G. Comprehensive overview of grid interfaced solar photovoltaic systems. Renew. Sustain. Energy Rev. 2017, 68, 316–332.
50. Solatialkaran, D.; Khajeh, K.G.; Zare, F. A Novel Filter Design Method for Grid-Tied Inverters. IEEE Trans. Power Electron. 2021, 36, 5473–5485.
51. Yagnik, U.P.; Solanki, M.D. Comparison of L, LC & LCL filter for grid connected converter. In Proceedings of the 2017 International Conference on Trends in Electronics and Informatics (ICEI), Tirunelveli, India, 11–12 May 2017; pp. 455–458.
52. Mohammad Reza, M.M. Performance Comparison of Synchronous Reference Frame-Based PLLs Topologies Under Power Quality Disturbances. Iran. J. Sci. Technol. Trans. Electr. Eng. 2018, 43, 307–321.
53. Pei, D.; Xia, Y. Robust Power System Frequency Estimation Based on a Sliding Window Approach Mathematical Problems in Engineering. Hindawi 2019, 2019, 1–98.
54. Sun, M.; Sahinoglu, Z. Extended Kalman filter based grid synchronization in the presence of voltage unbalance for smart grid. In Proceedings of the ISGT 2011, Anaheim, CA, USA, 17–19 January 2011; pp. 1–4.
55. Milano, F. A Geometrical Interpretation of Frequency. IEEE Trans. Power Syst. 2022, 37, 816–819.
56. Pal, B.; Sahu, P.K.; Mohapatra, S. A review on feedback current control techniques of grid-connected PV inverter system with LCL filter. In Proceedings of the 2018 Technologies for Smart-City Energy Security and Power (ICSESP), Bhubaneswar, India, 28–30 March 2018; pp. 1–6.
57. Guo, W.-Q.; Wu, W.-Y. Improved current regulation of three-phase grid-connected voltage-source inverters for distributed generation systems. IET Renew. Power Gener. 2010, 4, 101–115.
58. Akagi, H.; Watanabe, E.H.; Aredes, M. Instantaneous Power Theory and Applications to Power Conditioning; Wiley-IEEE Press: Piscataway, NJ, USA, 2017.
59. ORourke, C.J.; Qasim, M.M.; Overlin, M.R.; Kirtley, J.L. A Geometric Interpretation of Reference Frames and Transformations: dq0, Clarke, and Park. IEEE Trans. Energy Convers. 2019, 34, 2070–2083.
60. Teodorescu, R.; Liserre, M.; Rodriguez, P. Grid Converters for Photovoltaic and Wind Power Systems; Wiley-IEEE Press: Piscataway, NJ, USA, 2011.
61. Meral, M.E.; Celik, D. Mitigation of DC-link voltage oscillations to reduce size of DC-side capacitor and improve lifetime of power converter. Electr. Power Syst. Res. 2021, 194, 107048.
62. Teodorescu, R.; Liserre, M.; Rodriguez, P. Grid Converters for Photovoltaic and Wind Power Systems; John Wiley & Sons: Chichester, WS, UK, 2007; Chapter 10; pp. 237–287.