

Overview of Fault Ride-Through Requirements for Photovoltaic Grid Integration, Design and Grid Code Compliance

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Abstract—The integration of photovoltaic systems into the power grid and their dynamics through grid faults became an essential concern in grid codes' emerging requirements. Accordingly, fault ride-through of the grid-connected PV system functionality and regulation became the most critical grid codes considerations. Countries have come up with several stringent requirements for grid integration of renewable energy sources. This paper identified many FRT stipulations under grid fault conditions in various grid codes. The study examines the impact of PVs on the grid code development, offering a detailed and classified viewpoint on the FRT regulations and providing valuable details about the FRT capabilities of a common grid code to be used and referred. Consequently, this work proposes several grid-level design considerations to fulfill FRT requirements.

Keywords—*Fault Ride-Through; PV Grid Integration; Grid Codes*

I. INTRODUCTION (HEADING 1)

Renewable energy sources (RESs) have attracted researchers' and investors' attention due to the energy crisis and environmental issues [1]. Similarly, the demand for renewable energy has risen intensely over the years due to fossil fuel scarcity and greenhouse effects. By 2030, the market share of renewable energy production is projected to hit 20 percent. Solar photovoltaic (PV) and wind energy have become the most commonly used and challenging at the same time, due to advancements in power electronics interface techniques [2]. Due to its suitability in distributed generation, satellite systems, and transportation, the PV system is considered the most promising technology. Furthermore, PV sources are used in many systems today because they have the advantages of being maintenance-free and pollution-free. Over the past 20 years, the demand for solar electricity has steadily grown by 20-25 percent per annum, mainly due to falling costs and prices [3] [4]. Over the past few years, the solar industry's rapid growth has broadened the value of PV device design and deployment for more stable and efficient service, especially with the utility power grid. Consequently, the grid deployment regulations would still need to be updated such that more and more PV systems will be used in the grid.

Network operators describe the Grid code as guidelines, which specify the privileges and obligations of all generators and loads within the transmission and distribution system. Grid codes mainly did not contain any RES rules in the past, as the penetration levels were low compared to traditional generation [5] [6]. Over the last decade, however, the condition has changed dramatically, as many countries have experienced a massive rise in RES's amount and capability in their electric networks. The increasing prevalence of these energy sources in the electrical grid has deepened the prevailing technical concern of power system operators

regarding their impact on the grid' stability [7]. Consequently, RES's grid-connected operation requirements as a distributed generation (DG) systems in all national grids become increasingly restrictive, with less flexibility [8]. Grid operators can interpret the grid code regulations to find all generating unit responsibilities and load connected to the transmission or distribution network [9] [10]. Additionally, when a grid fault occurs, it causes a voltage dip, and the detection of such causes the disconnection of the PV power plant to shield the plant from the detrimental effects of voltage drop. This PV system disconnection poses an adverse influence on the remaining generation systems and detrimental to the overall system stability. Therefore, the grid codes prescribe FRT requirements to avoid this problem [11] [12].

Meeting this FRT specification is essential in ensuring the reliability and efficiency of the power grid. Grid-connected RESs disconnect from the grid throughout grid failures due to negligible impact on the grid in the past [13]. However, this disconnection is now unacceptable since PV power contributes substantially to the entire power generation. The current grid code thus demands that the PV power station stays connected under various fault conditions. Present grid codes demand RESs to sustain various grid disturbances and support network stability and ancillary services in a way similar to conventional generation units [14]. The grid code usually deals with grid specifications such as FRT standards, specifications for reactive current supply amid voltage dips, active power and frequency regulation, voltage, and frequency operating range, controlling reactive power and voltage, safety, and power quality problems flicker harmonics [15]. The updated grid code demands that the PV power station tolerate grid disruptions and simultaneously contribute to the system's generation of active and reactive power to deliver electricity efficiently. Special restrictions for these stations' operations during faulty grid conditions have ensured significant amendments in the original grid code specifications. Such specifications define the fault limits between those by which a generating system remains connected to the grid, resulting in different voltage profiles that stipulate the voltage sag depth and clearance period, which must be resisted. While the FRT specifications are somewhat different in the various standards, the first problem that generation systems have to manage when a voltage drop happens is restricting their transient reaction to prevent their defensive disconnection from the network.

Due to the rising penetration of wind turbines into the power grid, FRT was used for wind systems before the PV system. The FRT is, therefore, practical in the PV system recently, since the PV global penetration nearly doubled compared to the wind system penetration [16]. Many research studies have carried out analyses of FRT strategies to create and manage wind systems in both DFIG and PMSG

technologies. The grid code specifications for the wind turbine by the grid have been worked on. However, the different grid code specifications for FRT have not been evaluated for the PV system. Furthermore, no summary of various grid codes' FRT requirements is performed to assess the individual regulations, engagement rules, and design considerations. Consequently, the work presents comparative FRT grid code requirements for PV integration in countries and presented comprehensive grid-level design considerations for the integration of large-scale PV systems.

II. COUNTRIES' REQUIREMENTS

The FRT ensures that every power plant's ability to stay connected under specific limits during fault situations or low voltage [17]. E.ON and VE-T first suggested FRT specifications in 2003 German transmission operators. This condition is generally called FRT, and the voltage vs. time characteristics shown in Figure 1. The PV power plant should also deliver reactive power during voltage sags to improve the PCC voltage level until system stability is regained after clearance of fault. The disengagement of RESs beneath 80% of the rated voltage allows an unacceptable portion of the lost energy output. They are revised in several countries as a consequence of increased efficiency and PV systems penetration levels. The overall FRT specifications of PV schemes concentrate on maintaining sustained grid-connection of DC-AC inverters without over-current generation but, in the meantime, offer dynamic reactive power support to aid grid recovery under different faulty conditions [18]. Because of its benefits in voltage recovery and frequency stability, the FRT requirements are accepted and widely spread, ignoring the impacts of a high-penetration grid on transient stability.

A. Low Voltage Ride-Through

The grid codes specify that the Solar PV should tolerate grid voltage sag to a certain fraction of rated voltage, as in some instances, for a specified time down to zero [19] [20]. PV units will typically operate within this period without any disconnection. After removing faults, the PV system needs to quickly maintain active and reactive power to pre-fault value. Some codes stipulate that, like conventional synchronous generators, the PV system must supply the grid with the reactive current to support the grid voltage [21]. Figure 1 presents a sample of the LVRT capability curve. The grid codes LVRT curves of various countries are comparatively similar, with variance in their features and specific requirements. Whenever a generating unit is operating in

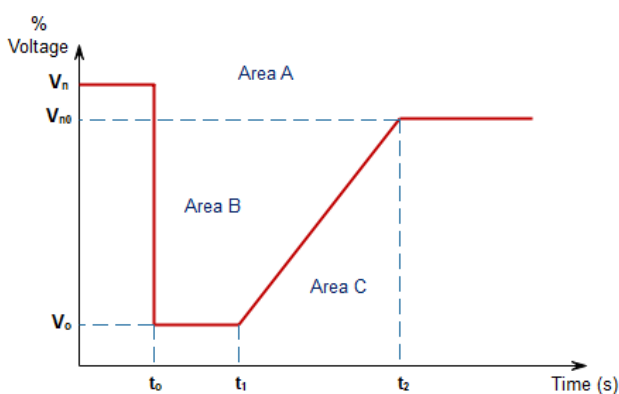


Fig. 1; generic FRT/LVRT curve

normal mode (V_n), its PCC voltage is in area A. When there is a fault occurring at time t_0 , the generating unit encounters a voltage sag (V_o) at the PCC. Generating units in area B have to endure the voltage drop until a particular time and remain grid-connected. If the generating unit experiences a substantial voltage decrease in which the voltage exceeded region C, the generating unit has the freedom to detach from the power grid. Upon removal of fault at the time past period (t_2), the voltage is requested to return to V_1 . Various grid code operators decide their own required time for their respective grid-connected units to withstand different levels of voltage sags, possibly up to 0 V, for a considerable period [22].

The German grid code [23] specified the FRT when the voltage drops to zero for a maximum duration of 150 ms, followed by the voltage recovery to 90 percent of the nominal voltage at PCC in 1.5 seconds, as revealed in Figure 2. Germany gives incentives to renewable energy farm operators to possess FRT enhancements and capabilities. The LVRT grid code for Germany comprises two lines. For example, the RES system must not disconnect from the grid over Germany borderline 1 line [24]. The disconnection of generating unit at voltage sag values of above borderline 1 may lead to instability. The voltage sags within borderlines 1 and 2 are encouraged to be ridden through. However, a plant may temporarily detach and rejoin for up to 2 seconds when a fault occurs between borderlines. This is usually determined based on an agreement between the plant owners and network operators. The energy-generating unit can always disconnect shortly below the borderline 2 lines. Units are not expected to disconnect under a 0% voltage drop that only persists for a duration less or equal to 150 microseconds. However, the requirement stipulates the compulsory disconnection of the grid-connected system for any condition under the blue line, as shown

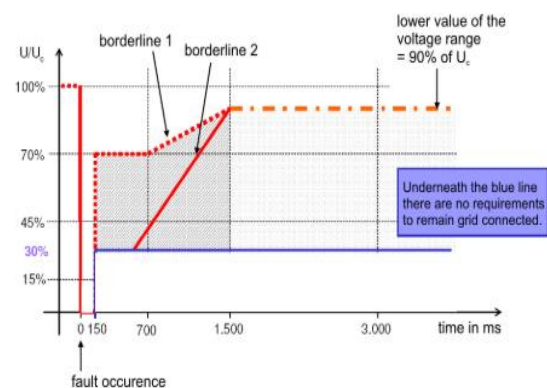


Fig. 2. LVRT Curves of Germany

The solar PV systems must withstand faults while still connected to the grid within 200 microseconds when the voltage at the PV system's connection point drops to zero in the Italian grid code. If the voltage at the connection point is recovered to 85% of the rated voltage within 1.5 s after fault occurrence, the photovoltaic units shall remain in continuous operation without disengagement. The Spanish grid code requirements are less cumbersome than German, which requests PV systems to withstand grid disturbance with 20% voltage sag for 500 ms with a voltage restoration stipulation of up to 80% in the subsequent period of 1 s [13]. Spain, just like Germany, gives incentives to energy generating units operating with FRT capability. The Danish grid code

concerning wind farms is used for the PV system. FRT specifications for classification of grid codes such as those in France rely heavily on the fault occurrence voltage level.

The grid code in Japan implements one of the world's highly restrictive FRT regulatory requirements. The generating units in Japan must remain grid-connected for up to 0 percent of the rated voltage for 1 second under different types of faults and return to an acceptable voltage level after up to 2 seconds. Subsequently, the voltage must rise to a convenient value after the fault at 3.5 seconds. The US grid code requires the voltage to decrease to zero for 625 microseconds and afterward reduce to 15 percent of the rated voltage value accompanied by the voltage recovery to 90% in 3 s. The Australian grid code also comes with strict stipulations, which require a drop in voltage to 0 % should last within a period of 450 microseconds. This also requires an increase in the voltage to 80 percent after recovery. FRT specifications for classification of grid codes such as those in India also rely heavily on the fault occurrence voltage level. The South African grid code LVRT requires the generating units not to disconnect from the grid for voltages above the LVRT curve if power clearing capability after the fault is sustained. These stipulations apply to different fault types, and the minimum voltage which the LVRT curve signifies is applicable in all the phases. The generating units are expected to reconnect to the grid within 1 second after the voltage recovery to 90 % of the rated grid voltage after disconnecting.

Table 1 summarizes the prescribed LVRT requirement for PV grid integration in the countries.

TABLE I. LVRT REQUIREMENTS IN COUNTRIES

	National Grid Codes	Fault		Post Fault	
		V_{min} (pu)	t_{max} (ms)	V_{min} (pu)	t_{max} (ms)
1	South Africa	0.00	150	0.85	2000
2	Spain	0.20	500	0.80	1000
3	Italy	0.00	200	0.85	1500
4	Japan	0.30	1000	0.80	1500
5	Germany (3 phase)	0.00	150	0.90	1500
6	United States	0.15	625	0.90	3000
7	United Kingdom	0.15	140	0.90	2500
8	Australia	0.00	450	0.80	450
9	Ireland	0.15	625	0.90	3000
10	Belgium (small voltage dips)	0.70	1500	0.92	1500
11	Belgium (large voltage dips)	0.00	200	0.92	700
12	New Zealand	0.00	140	0.90	3000
13	Sweden (< 100 MW)	0.25	250	0.90	250
14	Sweden (> 100 MW)	0.00	250	0.90	750
15	Canada (Hydro-Quebec)	0.00	150	0.85	2000
16	Denmark	0.10	500	0.85	1500
17	Hungary (3 phase)	0.45	150	0.90	1500
18	China	0.00	150	0.90	2000
19	Taiwan	0.15	625	0.90	3000
20	Norway (nominal < 220 kV)	0.00	400	0.85	1000
21	Norway (nominal \geq 220 kV)	0.15	200	0.90	1000
22	Greece	0.15	150	0.90	1500
23	Poland	0.15	600	0.80	3000
24	Finland	0.00	250	0.90	750
25	India	0.15	300	0.85	3000
26	France (400kV)	0.00	150	1.00	1500

27	France (63-225kV)	0.05	250	0.90	1100
28	Turkey	0.15	500	0.90	3000
29	Romania	0.15	625	0.90	3000
30	Cyprus	0.15	650	0.90	3000

B. High Voltage Ride-Through

Sometimes, a single line to ground fault and the switching of large power-factor-correction-capacitor banks causes a swell in the grid voltage [25]. However, compared to grid voltage sags, a surge in the grid voltage resulting from these grid disturbances is less frequent. HVRT capability is less acknowledged in the grid codes due to the extreme protection difficulties. The HVRT stipulation prescribes that generating units must possess HVRT capability to sustain a grid voltage swell while the remaining grid-connected under such condition [26]. However, most grid codes do not set out the rules for HVRT capability. The HVRT guidelines obtainable are set out in Figure 3 and Table 2. Under this transient period, the generating unit's resiliency strongly depends on its components' dynamic features.

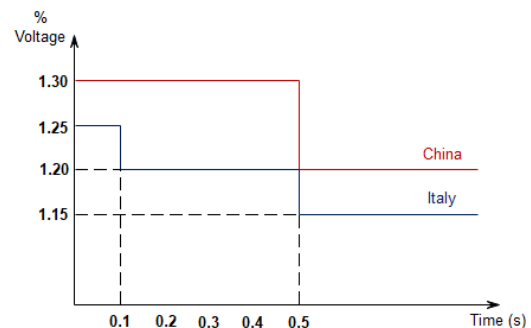


Fig. 3. HVRT Curves for Italy and China

TABLE II. HVRT REQUIREMENTS IN COUNTRIES

	National Grid Codes	Fault	
		V_{max} (pu)	t_{max} (ms)
1	China	1.30	500
2	Spain	1.30	250
3	Italy	1.25	100
4	Germany	1.20	100
5	Denmark	1.20	100
6	Australia	1.30	600
7	United States	1.20	1000

Grid codes solve this problem by stipulating the generating unit's HVRT specifications, which have no synchronous generators to keep the network safe and efficient. The HVRT specifications are clarified in Table 2 for the listed countries. Spain, Australia, and China have the most stringent regulations requiring a PV system to withstand a voltage swell of 130% of rated grid voltage. The Italian CEI 0-21 allows a PV device to sustain disruptions and to remain grid-tied under 125% voltage swell within 100 ms; the stipulated grid voltage recovery of 115 % is required in 500 ms [27].

C. Dynamic Grid Voltage Support

Ensuring voltage stability in the grid is crucial to meeting the FRT requirement, and this is therefore achieved by dynamic grid support during voltage drops or voltage swell. Consequently, generating units must be capable of: remaining grid-connected in the event of a grid fault, supporting the voltage by providing reactive power (inductive or capacitive) during the fault, and consuming the same or less reactive power after clearance of the fault.

For instance, the PV system is expected to inject a considerable amount of reactive current at the PCC during LVRT and HVRT operation, as given in Figure 4. This additional reactive current is crucial to mitigating voltage sag or swell in the case of faults. In Figure 4, the dynamic voltage support operation is activated in the event of a voltage drop of more than $\pm 10\%$ of the nominal voltage. Depending on the voltage sag depth, the grid code stipulates possible reactive current supply at least 100% of the rated current, as shown in Figure 2. The grid codes require that PV systems through their interface power electronic inverters to actively participate in the faster restoration of the grid voltage by generating reactive power during grid fault within the inverter apparent power limit [28] [29].

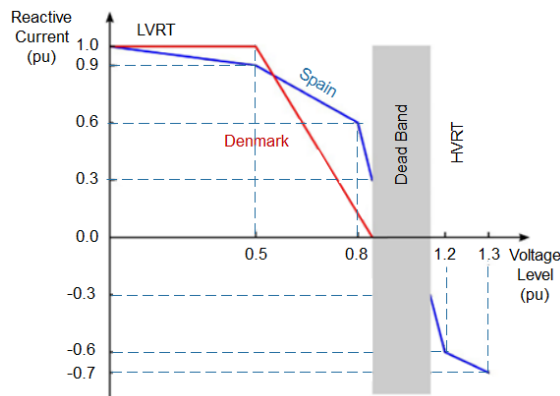


Fig. 4. Dynamic voltage support under grid faults

The grid codes of Spain, Germany, and Denmark stipulate that the reactive current can only be injected outside the dead band (between 0.90 pu and 1.10 pu of the nominal voltage) by $\pm 10\%$ [23]. The maximum time expected for dynamic voltage support operation to be activated after the inception of faults between 20 to 30 microseconds. After the fault clearance, the PV system should avoid reactive current absorption to prevent undesirable consequences. For instance, in the Spanish grid code, the PV generating unit is expected to be disconnected in the event of a fault, which caused voltage swell above 130 % of the nominal voltage [17] [30].

III. PROPOSED DESIGN REQUIREMENT

The new PV generating entries must make adequate preparation for FRT amidst evolving grid code regulations. Henceforth, grid-connected PV systems are encouraged to possess reactive power injection capability at the PCC under the previous sections' grid code stipulations. The future grid-connected PV systems will be required by the grid operators to remain connected under the period of fault as well as the steady-state grid condition. The reactive power limit is expected to operate within the apparent/complex power limits of the interfacing PV inverter such that the apparent power limit is not exceeded. Thus, the active power is limited to pave the way for the injection of reactive power at the PCC. This should be done within the shortest possible time as soon as the fault is detected [31]. This will ensure prompt injection and limitation of reactive power and active power, respectively. Several short-term and long-term energy storage equipment has been used at the instances of fault to limit the active power injection. This work suggests the PV systems' operation at an operating point other than the MPPT to limit the active power harvested from the PV. Therefore,

the non-MPPT operating point should correspond to the voltage sag's depth caused by the grid fault.

The PV system should always comply with the grid code stipulated power factor percentage at the PCC at steady-state operation [32]. Hence, PV is required to either inject or absorb reactive power to comply with the normal operation's stipulated power factor. Similarly, following the FRT stipulations of various countries examined in this work, the PV system must also inject and absorb reactive power for LVRT and HVRT applications. In a situation where PV inverters are operated in parallel, the PV inverters must be coordinated centrally to inject the required reactive current depending on the extent of voltage sags. This will be a challenge when the PV is operated in a microgrid with a local load, which also requires reactive power and active power irrespective of the transient grid condition. Furthermore, each PV inverter should operate within the limits of their respective apparent power capacity. Dynamic and static grid supports for FRT and power factor should not be contradicted, as one is required under dynamic grid condition, and the latter is required under steady-state condition. Hence both capabilities are required.

The loss of generation must be resisted under transient disturbance; therefore, the PV architecture must comply with the FRT requirement. The power electronic interface is essential in PV grid integration. The inverter system (central, single-string, and multi-string), the DC link (single stage or double stage), and backup DC-link energy storage significantly affect the FRT compliance. Consequently, the DC link voltage level and the active power parameters determine the inverter system of choice.

IV. CONCLUSION

Nowadays, RES plays a significant role in the power system, and because of the RES penetration growth, this role's importance increases. In this review work, various national grid code requirements for FRT capabilities are compared, analyzed, and reported. LVRT and HVRT, in most instances, are similar as they are all piecewise curves with stipulations of different depths of voltage that PV generating units are expected to either remain grid-connected or disconnect from the grid. Almost all of the selected countries possess the minimum recovery time. However, these standards and specific stipulations vary from country to country. During fault occurrence, the duration of PVs to remain connected to the grid is distinctive for any grid code. The grid codes examined to show that there are various distinctions in grid codes, and in some of the countries where they have nearly similar features. Grid codes voltage-time curves are primarily dependent on grid configurations and network design. So the FRT capabilities of the comparative curves vary.

Dynamic voltage support is distinct from static voltage supports, and they must not be confused with each other. The latter is concerned with power factor correction under steady-state operation. In contrast, the former is concerned with the dynamic operation of the generating system, especially in the event of a grid fault. All the grid codes are cohesive, and all agreed on the optimal grid supports for stability and rapid responses under grid disturbance. However, all the requirements imposed on the PV generating systems are done to the grid operators' advantage and at the expense of the power electronic inverter interfacing the PV modules with the grid. Consequently, interface inverters are poised to face

numerous challenges in their designs and grid-connected operation. The inverter will be expected to promptly adjust their active and reactive current references in fulfilling the FRT requirements. This, therefore, possess potential voltage instability and overcurrent issues for the inverter system. Hence this work proposed certain grid-level design considerations for the PV systems. This will ensure that the overall grid system is operated in an efficient and resilient way.

REFERENCES

- [1] B. N. Alajmi, K. H. Ahmed, G. P. Adam, and B. W. Williams, "Single-phase single-stage transformer less grid-connected PV system," *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 2664–2676, 2013.
- [2] M. T. Elsir, M. A. Abdulgali, A. T. Al-Awami, and M. Khalid, "Sizing and allocation for solar energy storage system considering the cost optimization," in *8th International Conference on Renewable Energy Research and Applications, ICRERA 2019*, 2019, pp. 407–412.
- [3] K. Gillingham and T. Tsvetanov, "Hurdles and steps: Estimating demand for solar photovoltaics," *Quant. Econom.*, vol. 10, no. 1, pp. 275–310, Jan. 2019.
- [4] K. C. Wijesinghe, "Optimized integration of solar PV energy on to telecom power systems for DC and A/C buses or energy storages with proposed converters to make them as profit centers," in *8th International Conference on Renewable Energy Research and Applications, ICRERA 2019*, 2019, pp. 545–550.
- [5] M. Mohseni and S. M. Islam, "Review of international grid codes for wind power integration: Diversity, technology and a case for global standard," *Renew. Sustain. Energy Rev.*, vol. 16, no. 6, pp. 3876–3890, 2012.
- [6] S. Sewchurran and I. E. Davidson, "Guiding principles for grid code compliance of large utility scale renewable power plant intergration onto South Africa's transmission/distribution networks," in *2016 IEEE International Conference on Renewable Energy Research and Applications, ICRERA 2016*, 2017, pp. 528–537.
- [7] M. Bajaj and A. K. Singh, "Grid integrated renewable DG systems: A review of power quality challenges and state-of-the-art mitigation techniques," *Int. J. Energy Res.*, vol. 44, no. 1, pp. 26–69, Jan. 2020.
- [8] A. Luna *et al.*, "Grid Voltage Synchronization for Distributed Generation Systems Under Grid Fault Conditions," *IEEE Trans. Ind. Appl.*, vol. 51, no. 4, pp. 3414–3425, 2015.
- [9] J. M. Aga and H. T. Jadhav, "Improving fault ride-through capability of DFIG connected wind turbine system: A review," *Proc. 2013 Int. Conf. Power, Energy Control. ICPEC 2013*, pp. 613–618, 2013.
- [10] I. E. Davidson and R. Reddy, "Performance Evaluation of Solar Roof-Top PV on Eskom's LV Electric Power Distribution Networks," in *7th International Conference on Smart Grid, icSmartGrid 2019*, 2019, pp. 97–102.
- [11] E. Buraimoh and I. E. Davidson, "Modelling and Assessment of the Fault Ride- Through Capabilities of Grid Supporting Inverter-Based Microgrids," in *Clemson University Power Systems Conference (PSC 2020)*, 2020, pp. 1–7.
- [12] E. Buraimoh and I. E. Davidson, "Modeling and Analysis of Standalone Inverter-Based Microgrid with Grid-Supporting Voltage-Source Control under Changing Load," in *2020 IEEE PES/IAS PowerAfrica*, 2020, pp. 1–5.
- [13] A. B. Rey-Boué, N. F. Guerrero-Rodríguez, J. Stöckl, and T. I. Strasser, "Modeling and Design of the Vector Control for a Three-Phase Single-Stage Grid-Connected PV System with LVRT Capability according to the Spanish Grid Code," *Energies*, vol. 12, no. 15, p. 2899, Jul. 2019.
- [14] E. Buraimoh, I. E. Davidson, and F. Martinez-Rodrigo, "Fault Ride-Through Enhancement of Grid Supporting Inverter-Based Microgrid Using Delayed Signal Cancellation Algorithm Secondary Control," *Energies*, vol. 12, no. 20, p. 3994, Oct. 2019.
- [15] E. Kurt and G. Soykan, "Performance analysis of DC grid connected PV system under irradiation and temperature variations," in *8th International Conference on Renewable Energy Research and Applications, ICRERA 2019*, 2019, pp. 702–707.
- [16] A. Q. Al-Shetwi, M. Z. Sujod, F. Blaabjerg, and Y. Yang, "Fault ride-through control of grid-connected photovoltaic power plants: A review," *Sol. Energy*, vol. 180, no. November 2018, pp. 340–350, 2019.
- [17] K. Loudiyi, A. Berrada, H. G. Svendsen, and K. Mentessidi, "Grid code status for wind farms interconnection in Northern Africa and Spain: Descriptions and recommendations for Northern Africa," *Renewable and Sustainable Energy Reviews*, vol. 81. Elsevier Ltd, pp. 2584–2598, 01-Jan-2018.
- [18] A. Del Pizzo, L. P. Di Noia, and S. Meo, "Super twisting sliding mode control of smart-inverters grid-connected for PV applications," 2017, pp. 793–796.
- [19] A. Q. Al-Shetwi, M. Z. Sujod, and N. L. Ramli, "A review of the fault ride through requirements in different grid codes concerning penetration of PV system to the electric power network," *ARPJ. Eng. Appl. Sci.*, vol. 10, no. 21, pp. 9906–9912, 2015.
- [20] E. Buraimoh and I. E. Davidson, "Investigation of the Low Voltage Ride-Through of Inverter Using Virtual Inertia Methods in Microgrid," *Int. J. Eng. Res. Africa*, vol. 44, no. 1, pp. 200–212, 2019.
- [21] S. Sakurai, O. Sakamoto, and T. Nitta, "Linearized model of power system with synchronous generator, variable renewable energy generation and load," in *8th International Conference on Renewable Energy Research and Applications, ICRERA 2019*, 2019, pp. 276–279.
- [22] M. T. Hagh and T. Khalili, "A review of fault ride through of PV and wind renewable energies in grid codes," *Int. J. Energy Res.*, vol. 43, no. 4, pp. 1342–1356, 2019.
- [23] M. G. Taul, X. Wang, P. Davari, and F. Blaabjerg, "Current Reference Generation based on Next Generation Grid Code Requirements of Grid-Tied Converters during Asymmetrical Faults," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 19, pp. 1–1, Jul. 2019.
- [24] M. Tsili and S. Papanthassiou, "A review of grid code technical requirements for wind farms," *IET Renew. Power Gener.*, vol. 3, no. 3, pp. 308–332, 2009.
- [25] A. F. Bastos, K. W. Lao, G. Todeschini, and S. Santoso, "Accurate Identification of Point-on-Wave Inception and Recovery Instants of Voltage Sags and Swells," *IEEE Trans. Power Deliv.*, vol. 34, no. 2, pp. 551–560, Apr. 2019.
- [26] S. Fan, P. Chao, and F. Zhang, "Modelling and simulation of the photovoltaic power station considering the LVRT and HVRT," *J. Eng.*, vol. 2017, no. 13, pp. 1206–1209, Jan. 2017.
- [27] G. M. Tina and G. Celsa, "Active and reactive power regulation in grid-connected PV systems," in *Proceedings of the Universities Power Engineering Conference*, 2015, vol. 2015-November.
- [28] A. Anurag, Y. Yang, and F. Blaabjerg, "Thermal Performance and Reliability Analysis of Single-Phase PV Inverters with Reactive Power Injection Outside Feed-In Operating Hours," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 3, no. 4, pp. 870–880, Dec. 2015.
- [29] Y. Yang, H. Wang, and F. Blaabjerg, "Reactive power injection strategies for single-phase photovoltaic systems considering grid requirements," in *IEEE Transactions on Industry Applications*, 2014, vol. 50, no. 6, pp. 4065–4076.
- [30] Y. Yang, W. Chen, and F. Blaabjerg, "Advanced control of photovoltaic and wind turbines power systems," *Stud. Comput. Intell.*, vol. 531, pp. 41–89, 2014.
- [31] F. M. Aboshady, M. Sumner, and D. W. P. Thomas, "A Wideband Fault Location Scheme for Active Distribution Systems," in *7th International IEEE Conference on Renewable Energy Research and Applications, ICRERA 2018*, 2018, pp. 891–896.
- [32] D. Motyka, M. Kajanova, and P. Bracinek, "The Impact of Embedded Generation on Distribution Grid Operation," in *7th International IEEE Conference on Renewable Energy Research and Applications, ICRERA 2018*, 2018, pp. 360–364.