Tampere University

Ahmed Darwish

# MODERN TECHNICAL GRID CODES REQUIREMENTS FOR LARGE SCALE SOLAR PV POWER PLANTS

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# ABSTRACT

Ahmed Darwish: Modern technical grid codes requirements for large scale solar PV power plants
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Transition into vast contribution of intermittent renewables such as photovoltaic (PV) systems in power production is escalating rapidly around the globe. This huge penetration level of PV technology as a distributed energy resource has started to impact the operation, stability, reliability and security of power grids. They can disrupt the grid voltage, frequency, protection devices, reliability and power quality. Consequently, Transmission System Operators (TSOs) in many countries have driven to develop new requirements and specifications for their connection grid codes of the PV power plants. This is to address the issues of stability and security in the power network. These grid codes requirements demand specific technical functions that shall be supplemented with the PV inverters to perform in the same manner of conventional based power plants during the steady state and dynamic operation of the power network.

The main focus of this thesis is to draw a detailed comparison and analysis of the modern technical requirements and functions which are imposed in different international grid codes for interconnection of large scale PV power plants into their power networks. The comparison and analysis are implemented to identify the minimum technical requirements and functions which are required from PV power plants' owners, and to define the expected future requirements which have to be considered in the future design of PV inverters.

It is found from the comparison and analysis that the minimum modern technical requirements and functions of PV inverters in most of the grid codes are low voltage ride through (LVRT), reactive current support (RCS), voltage control and overfrequency regulation response. The LVRT requirement must be supplemented with RCS injection function to ride through the fault and remain connected to the grid during a limited period in case of voltage dip. The voltage control can be achieved with at least one mode of reactive power control mostly constant reactive power mode ($Q$ ($P$)). The overfrequency response requirement can be established by active power curtailment (APC) function by decreasing the active power of the PV power plant gradually with a configured droop so as to avoid excessive generation at the PCC.

Finally, the thesis also identifies the expected future technical requirements which shall be considered in the future design of the PV inverters to implement the same dynamic performance of the conventional synchronous power plants. These future requirements include high voltage ride through (HVRT), voltage control, underfrequency control response, virtual inertia capability (VIC), black start capability (BSC) and power oscillation damping (POD). The HVRT requirement must be supported with RCS absorption function during voltage swell. The voltage control requirement can also be implemented with constant voltage mode set point $Q(V)$ or with power factor mode set point $\cos \phi(P)$. During underfrequency disturbance, the active power reserve (APR) and ramp rate control (RRC) functions shall contribute to frequency regulation at the PCC. VIC, BSC and POD requirements are still not clearly stipulated in most of the grid codes. These future requirements still require more research and study to get the optimal design guidelines for the future PV inverters. Coordination between the countries by sharing resources, knowledge and experiences will be the main core to implement a global standard grid code that can harmonize these technical requirements to facilitate the integration of PV power plants and hence, support the PV owners to achieve the balance between the cost and the global standards and regulations.

Keywords: PV power plants, grid codes requirements, fault ride through, grid codes

# PREFACE

The work of this thesis has been implemented at the Department of Electrical Engineering of Tampere University during the period of Jan 2020 to October 2020 with one of the requirements to complete MSc. degree in Smart Grids (Electrical Engineering) from Tampere University.

I want to express my profoundest appreciation and gratitude to the supervisor of my thesis and examiner Prof. Seppo Valkealahti, for his guidance and support to complete the work and progress of this thesis during this exceptional time of COVID-19 pandemic. His notes, assistance and mental support have helped me to provide the road map to accomplish the work of my thesis during this exceptional period.

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Tampere, November 2020

Ahmed Darwish

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| AC | Alternating Current |
| APC | Active Power Curtailment |
| APR | Active Power Reserve |
| AGO | Agreed with Grid Operator |
| BESS | Battery Energy Storage System |
| BSC | Black Start Capability |
| DC | Direct Current |
| DG | Distributed Generation |
| DSO | Distribution System Operator |
| ENTSO-E | European Network of Transmission System Operators for Electricity |
| FRT | Fault Ride Through |
| HVRT | High Voltage Ride Through |
| IEA | International Energy Agency |
| LFSM-O | Limited Frequency Sensitive Mode of Overvoltage |
| LFSM-U | Limited Frequency Sensitive Mode of Undervoltage |
| LV | Low Voltage |
| LVRT | Low Voltage Ride Through |
| MPP | Maximum Power Point |
| MV | Medium Voltage |
| NS | Not Stipulated |
| OLTC | On Load Tap Changer |
| PCC | Point of Common Connection |
| POD | Power Oscillation Damping |
| pu | per unit |
| PV | Photo Voltaic |
| RCS | Reactive Current Support |
| ROCOF | Rate Of Change Of Frequency |
| ROCOP | Rate Of Change Of Power |
| RRC | Ramp Rate Control |
| SAIDI | System Average Interruption Duration Index |
| SAIFI | System Average Interruption Frequency Index |
| SCADA | Supervisory Control And Data Acquisition |
| SOC | State Of Charge |
| STATCOM | STATic synchronous COMpensator |
| THD | Total Harmonic Distortion |
| TSO | Transmission System Operator |
| UPS | Uninterruptable Power Supply |
| VIC | Virtual Inertia Capability |
| ZVRT | Zero Voltage Ride Through |

| | |
|---|---|
| $I$ | Current |
| $f$ | Frequency |
| $f_1$ | Frequency value 1 |
| $f_2$ | Frequency value 2 |
| $f_3$ | Frequency value 3 |
| $f_4$ | Frequency value 4 |
| $f_{max}$ | Maximum frequency limit |
| $f_{min}$ | Minimum frequency limit |
| $f_n$ | Nominal frequency or network frequency |
| $f_o$ | Frequency value over the dead band limit |
| $f_u$ | Frequency value under the dead band limit |
| $G$ | Solar insolation |
| $I_n$ | Nominal current |
| $I_q$ | Reactive current |
| $I_{q0}$ | Reactive current before fault |
| $k$ | Droop slope |
| $k_1$ | Droop slope 1 |
| $k_2$ | Droop slope 2 |
| $k_3$ | Droop slope 3 |
| $P_{res}$ | Active power reserve |
| $P_{min}$ | Minimum active power value |
| $P_n$ | Rated maximum active power capacity |
| $P_{present}$ | Present available active power |
| $Q$ | Reactive power |
| $Q_{max}$ | Maximum reactive power |
| $Q_{min}$ | Minimum reactive power |
| $T$ | PV module ambient temperature |
| $t$ | Time |
| $t_0$ | Time instant of voltage dip |
| $t_1$ | Time instant when voltage dip or swell fault is cleared |
| $t_2$ | Time instant to return the voltage to nominal value |
| $t_r$ | Time instant of voltage rise |
| $\pm V$ | Voltage dead band limits |
| $V_0$ | Voltage value during voltage dip |
| $V_1$ | Voltage nominal value after voltage dip or swell |
| $V_{max}$ | Maximum voltage value |
| $V_{min}$ | Minimum voltage value |
| $V_n$ | Nominal voltage |
| $V_r$ | Voltage rise value |
| $\Delta I_q$ | Change in reactive current |
| $\Delta V$ | Change in network voltage at PCC |
| $\cos \phi$ | Power factor |

# 1. INTRODUCTION

Conventional fossil fuel-based technologies play a prominent role in social development. They have enhanced our life quality, but at the same time, these developments have come at a dramatic price, leading to one of the most grave crises of all times, which is global warming [1]. Transition into renewables in the power production has a substantial impact to mitigate the climate change and global warming. The growth of renewables in electricity generation sector is notable as their contribution of installed power generation capacities has jumped to 33% in 2018 only [3]. Solar photovoltaic (PV) and wind power technologies as renewables are expanding promptly in many countries all over the world such as Germany, China, USA and Denmark. Recently, a vast amount of distributed solar PV power plants has been installed to the electric power system. It will accelerate the renewable capacity growth globally in the next years [3,5] . During the recent 10 years only, it can be observed that the power generation from the PV technology has increased rapidly from less than 50 GW to almost 500 GW of installed capacity as seen in figure 1.1. According to the International Energy Agency (IEA), the global installed capacity of the PV technology is expected to increase by 400 GW by 2024 as seen in figure 1.2. By this escalating rate, the power system in the future will have a reduced share of conventional synchronous based power plants with high and steady power generation capacity. In addition to that, it has increased share of the PV converter-based power plants which have volatile power generation capacity and zero rotational masses. Due to this huge penetration of converter-based PV distributed generation units to the electric power utility, the technical challenges and issues of stability, reliability and security of the electric power grid have aroused due to their intermittency nature [5]. Thus, Transmission System Operators (TSO) in many countries have started to impose grid codes requirements for the integration of solar PV power plants to enhance network safety, stability and reliability [6]. The purpose of these technical requirements is to demand specified functions that shall be supplemented with PV power plants to be able to perform the same as conventional power plants during normal operation and disturbances. The owner of the PV generation facility has to ensure these technical requirements according to the relevant grid code in each country before interconnection to the grid. Accordingly, grid codes over the world and their requirements for PV systems are still developing, like limitation of ramp rates and power curtailment in case of system overfrequency. Thus, it is necessary to foresee the coming requirements regarding the control and system integration of PV generation plants, especially in weak networks. As a result, the PV power plants' owners can considerate these expected technical requirements in their future design for PV inverters.

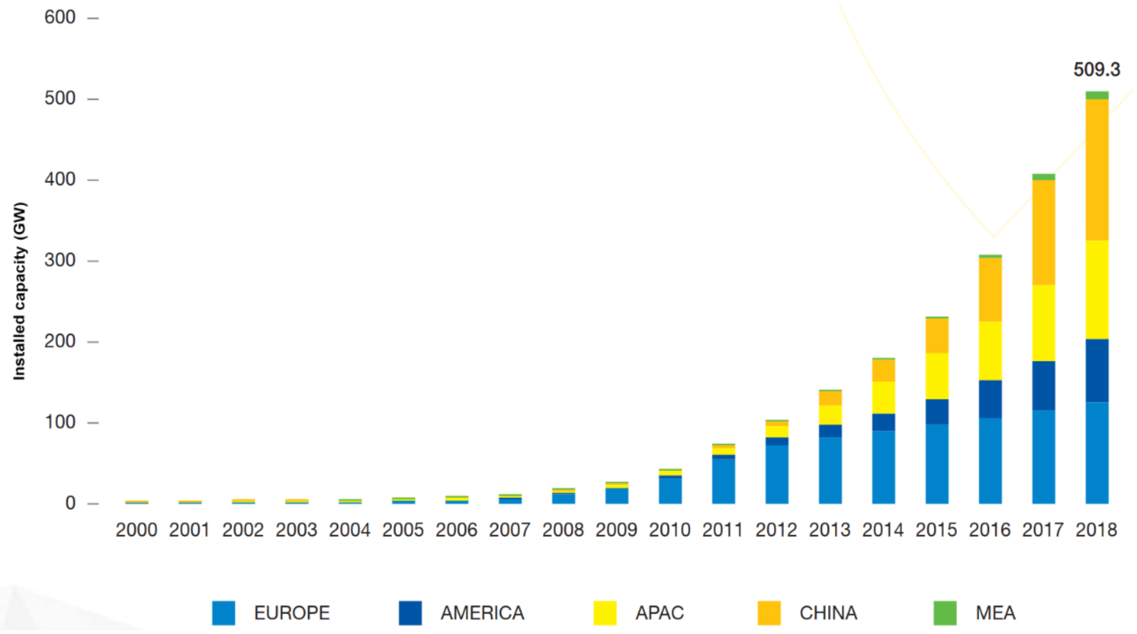


***Figure 1.1.*** *Global total solar PV installed capacity by region from 2000 to 2018* [2].

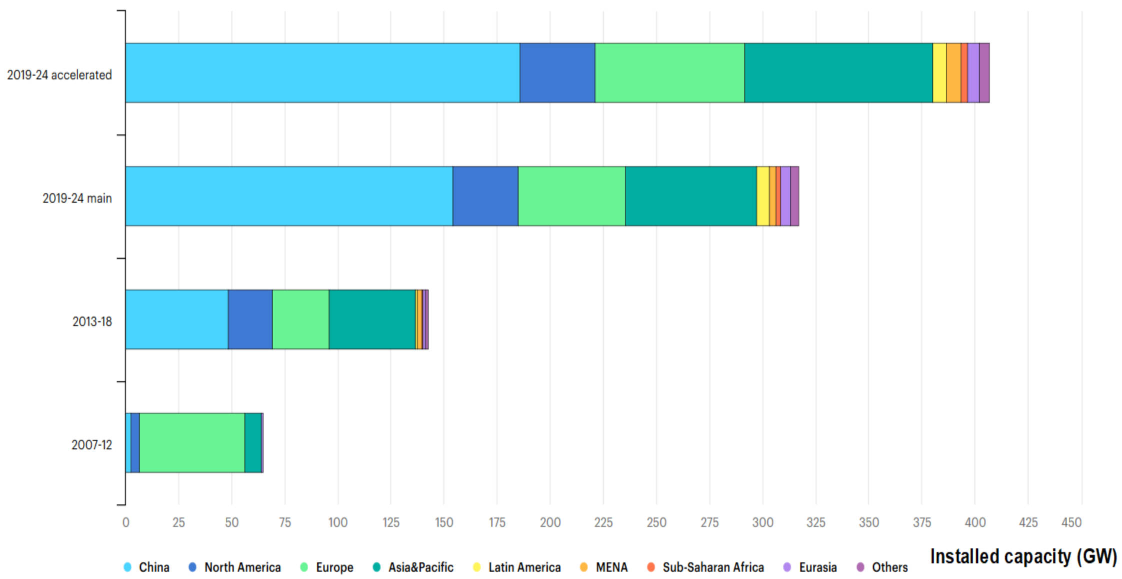


***Figure 1.2.*** *Distributed solar PV installed capacity growth and future scenarios by region from 2007-2024* [7].

## 1.1 Thesis objective

The core goals of this thesis are illustrated below:

- Discuss the impact of vast penetration of PV power plants on the power system, including frequency and voltage regulation, protection aspects, reliability and power quality.
- Compare and analyze the modern technical requirements which are stipulated in different international grid codes for PV power plants to interconnect with their power networks. These comparison and analysis include the technical specifications of fault ride through, reactive current support, reactive power and voltage control, active power and frequency control during steady state and dynamic operation.
- Determine the minimum technical requirements and functions which have to be supplemented with the PV systems' inverters according to the reviewed modern international grid codes.
- Identify the expected future technical requirements and functions for PV systems' inverters to emulate the same performance of conventional synchronous power plants to be considered in their future design to comply with each country grid code.

## 1.2 Thesis Scope

Grid codes stipulate the guidelines for the power system and energy market operation which can include planning codes, operating codes, policy rules, market guidelines and connection codes. These set of codes and guidelines are implemented to ensure the operational stability, grid security and well-functioning wholesale markets.

This thesis focuses only on the connection grid codes for the technical requirements of PV power plants to be integrated into the distribution and transmission networks. It concentrates on the medium and large scale PV power plants which can be connected at different voltage levels according to the network type in each country. The scope includes protection functions, control functions and regulation functions during normal and dynamic operation.

## 1.3 Thesis outline

Chapter 2 illustrates a short overview about the solar photovoltaic (PV) technology and power generation as well as an illustration about the current development and future investment in solar PV technology power production.

Chapter 3 discusses the impact of large scale PV systems as distributed generation units on transmission and distribution networks. It focuses on how the intermittency nature of PV systems can affect the aspects of network reliability, security and power quality such as voltage flickers, islanding operation and protection.

Chapter 4 implements a detailed comparison and analysis for the modern technical requirements and functions which are required in international grid codes from PV power plants. It determines the minimum present functions and requirements that shall be supplemented for PV inverters. It also demonstrates an overview about the advanced future technical requirements which are still under discussion and research so that it will lead to more development in most of the present international grid codes to request these requirements and functions from PV power plants in the future.

Chapter 5 displays a consecutive summary of the investigated requirements and functions with key considerations that have to be considered for each function in the future design of PV inverters.

Chapter 6 concludes the thesis and gives forth the future work to harmonize the grid codes globally by coordination between the countries and sharing experiences.

# 2. SOLAR PV TECHNOLOGY

In this chapter, a short overview about the solar photovoltaic (PV) technology, power generation and power plant configurations are discussed. An illustration about the current development and future investment in solar PV technology is also presented briefly.

## 2.1 Solar photovoltaic systems

Solar photovoltaic (PV) technology is the exploitation of the solar energy to produce a direct current electrical power using solar PV cells. PV cells can be devised of semiconductor materials like silicon which can be illuminated by the sunlight to generate electricity [8]. These individual PV cells are interconnected together in a framework for installation to form PV module. By connecting PV modules in parallel and in series, solar PV generator is constructed. As seen in figure 2.1, strings of modules are connected in series; to increase the voltage, then connected in parallel; to increase the current. Thus, PV generator output power can be enhanced [9]. Each string in series has a blocking diode and fuse for protection.

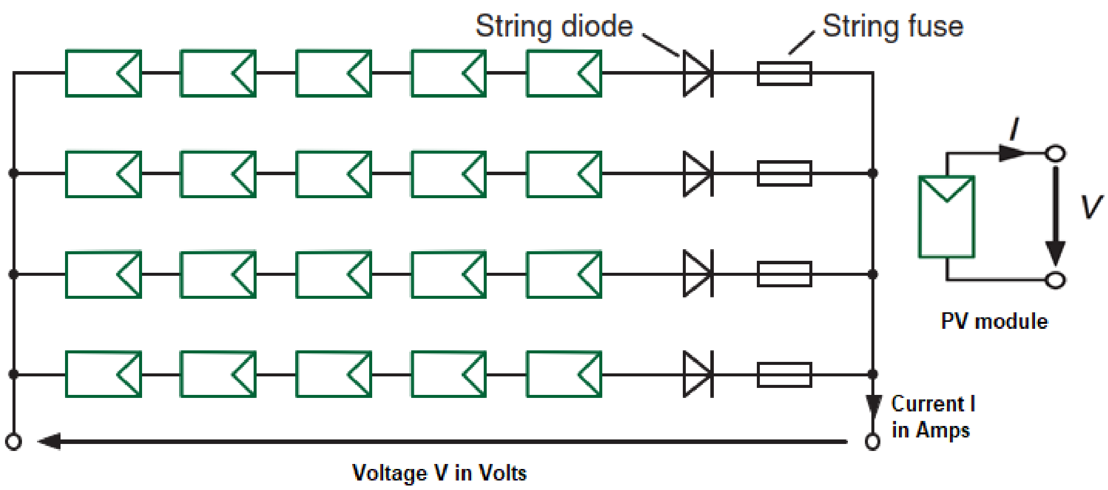


***Figure 2.1.*** *Basic structure of a solar PV generator with several strings of series connected PV modules connected in parallel* [9]**.**

Solar PV generator output performance is influenced by essential environmental factors such as irradiance intensity and module temperature. Therefore, the maximum power point (MPP) output of the PV module is dependent upon the insolation level and the surrounding temperature. Figures 2.2 and 2.3 illustrate the current-voltage (*I*-*V*) and power-voltage (*P-V*) characteristics at which the MPP increases when the module temperature decreases or when the insolation intensity increases. It can be noticed that at constant insolation *G* of 1000 W/m$^2$, the PV module output voltage decreases as the module ambient temperature increases as seen in figure 2.2. While, if the temperature (*T)* is constant at 25 °C, the PV module output current decreases as the insolation level decreases and also the PV module output voltage is slightly decreasing as seen in figure 2.3. In this manner, both module temperature and insolation intensity are influenced by other environmental circumstances such as cloud movement, ambient temperature, wind speed and direction. This clarifies the intermittency behavior of the solar PV system power output as it always tries to track its global MPP at non-homogenous insolation levels caused by the overpassing cloud shadows [10]. Accordingly, numerous MPPs can occur with a broad range of voltages, initiating a sever effect on the system operation as the PV inverter is no longer able to track the global MPP. Regarding the vast deployment of solar PV power plants into the power system, this intermittency nature can cause a considerable impact on the grid reliability, stability and power quality [11]. Regardless of these technical issues on the grid utility, high penetration of the photovoltaic systems applications is progressively remarked globally.

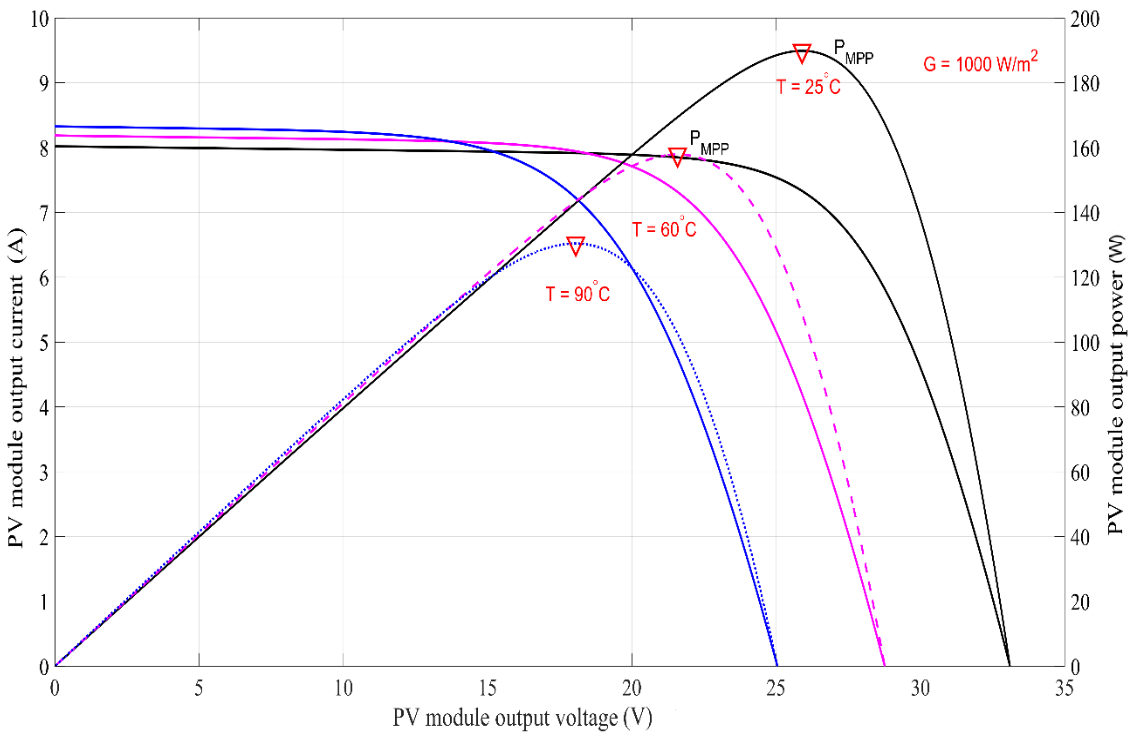


***Figure 2.2.*** *Solarworld SW1-165 module I-V and P-V characteristics at various module temperatures (T) at constant insolation G =1000 W/m$^2$.*

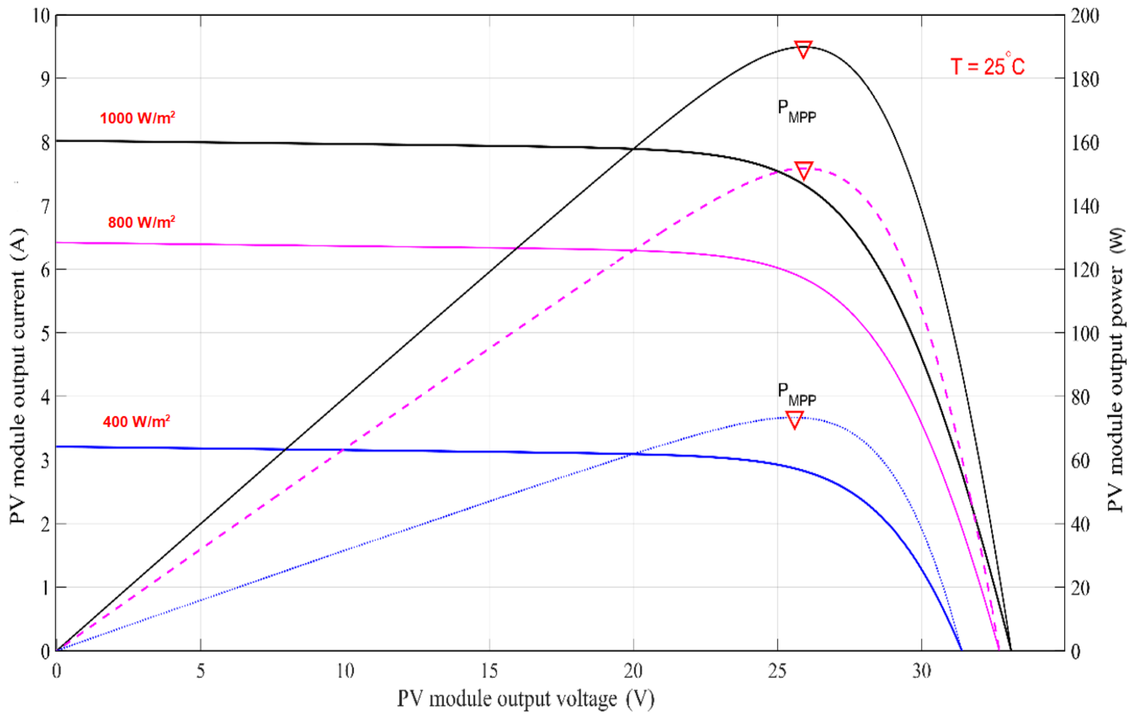


***Figure 2.3.*** *Solarworld SW1-165 module I-V and P-V characteristics at various insolation (G) at constant module temperature* $T$ = 25 °C.

PV power systems applications can be classified into three main divisions based on their functionality and operational requirements; off-grid, on-grid and hybrid PV systems. Stand alone or off-grid PV systems are mostly used for domestic or non-domestic applications to provide electricity for households and villages with low power loads such as lighting, refrigeration, water pumping and telecommunication. The battery storage system is essential for off-grid PV system to supply energy during lack of solar irradiance. In this case, a charge regulator and a power tracker can be used so as to maximize the PV power generation and to maintain possible maximum state of charge (SOC). An inverter is used to supply power for AC appliances.

Grid connected or on-grid PV systems provide the power to grid connected customer or directly to the electricity utility network. In this system, an inverter is used to convert the solar DC power into AC power, and they can be divided into two main categories. The first category is grid connected distributed PV systems which are used where the distribution network is constructed to provide the power for customers such as commercial, residential or industrial buildings. The second category is centralized PV systems which are typically ground mounted and they can execute centralized power functions independently [12].

Hybrid PV power systems combine the benefits of solar PV systems with diesel generators like, operating cost reduction. Recently, these systems have several applications that can be used for providing power to rural customers and telecom stations. In this system, the solar PV DC power is followed by bidirectional converter to charge the storage batteries and supply the AC power to the AC loads. The diesel generator can support the AC loads and the batteries in case of absence of the solar irradiance to fill the gap between the loads and PV generated power. Battery storages are used to enhance the overall system performance to ensure the balance between the demand and production. An intelligent energy management system can be used to control and regulate the overall operation and enhance performance. An overview about the global market of the solar PV installation and share is illustrated in the next section.

## 2.2 Solar PV technology trends and prospects

The growth of the world population as well as the advancement in living standards dictate the escalation of power generation requirements. Reliance on fossil fuels-based power plants is no longer secured and has led to scarcity and global warming. Therefore, necessity for renewable energy will continue to grow. It is driven by declining in costs of the used technology like PV, and necessity to reduce $CO_2$ emissions. Global investments in new renewable power applications have increased from less than 50 billion dollars in 2004 to almost 300 billion dollars in the recent years [13]. This exceeds the investments in new fossil fuel power plants by a factor of three in 2018 [14]. Wind power and solar PV have occupied 90% of total investments of renewable technology in 2018 [13]. The global market investment in the solar technology is emerging abruptly. For instance, in figure 2.4, solar PV technology, mostly grid connected, dominated the new global cumulative installed capacity by 56% compared to all other renewables [15]. The motivations given by the countries are escalating to broaden their market installation of PV technology as its cost reduction curve continues at a much faster pace than for any other technology. Today, generation cost for solar power is significantly lower than establishment of new nuclear or coal power plants. For example, China which dominates the global PV market share recently has installed up to 295 GW in the recent years. The newly added capacity is up to 71.3 GW in 2018 only which equals 58% of the global market share. USA is also sharing about 12% from the global market with cumulative installed capacity up to 62 GW in 2018. Germany dominates the solar PV market in Europe by 35% increase in 2019 from total European global cumulative installed capacity of 16.7 GW in 2019.

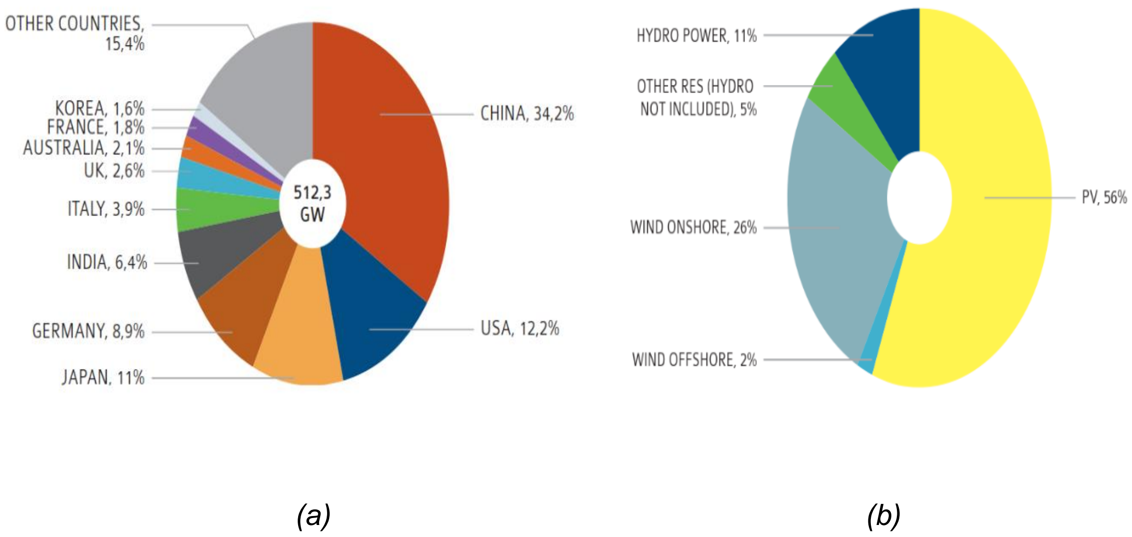


***Figure 2.4.*** *(a) Global cumulative PV installed capacity share percentage in 2018, (b) Global cumulative total share percentage of the new installed capacity of different renewable technologies in 2018* [15].

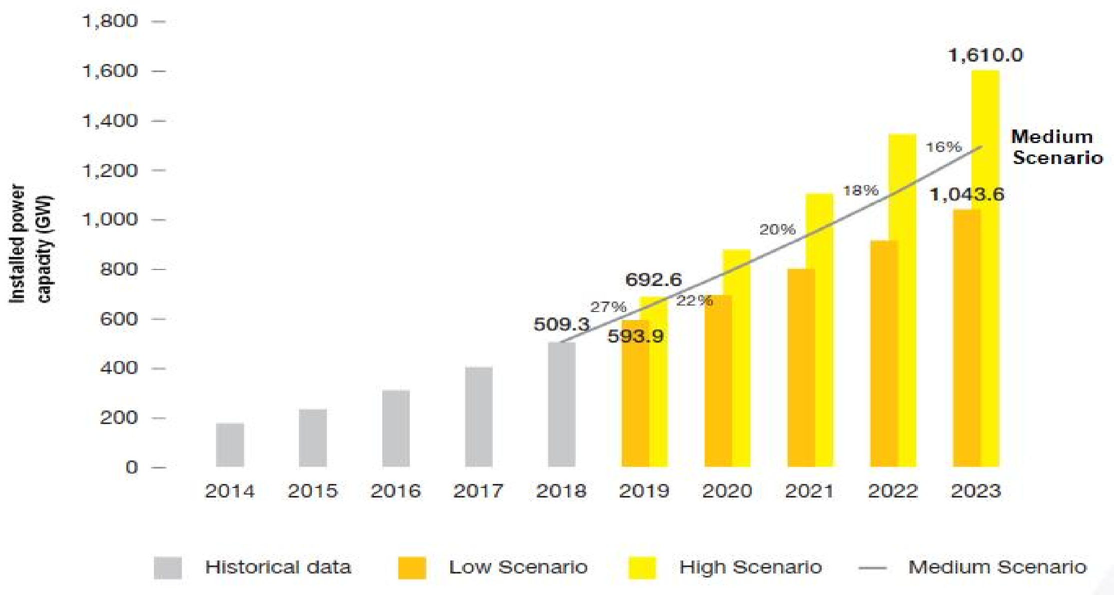


***Figure 2.5.*** *Global forecast scenarios of total installed power capacity of PV technology from 2014 to 2023* [2].

Middle East, Africa and Latin America have commenced to change their energy polices to evolve their market in solar PV power generation by solid share percentage. For example, Egypt has installed approximately 500 MW and Brazil has installed 1 GW in 2018. Accordingly, the development and investment in the PV technology seem unstoppable. It tends to increase by initiating incentive schemes and new energy polices as there is no alternative to this low cost and versatile clean power source that can be utilized for consumer, distributed and utility-scale applications. According to [2], forecasting medium scenario expects an outstanding leap of around 1 TW of global installed PV generation capacity by 2023 as seen in figure 2.5.

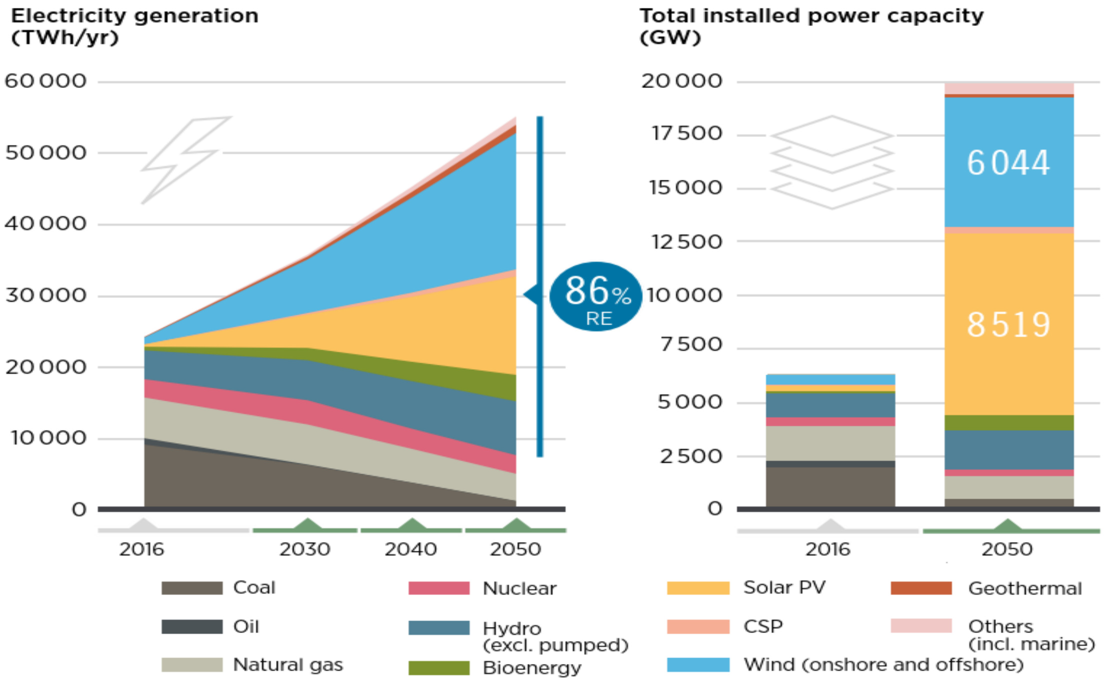


***Figure 2.6.*** *Global forecast for electricity generation from different technologies on the left (RE: Renewables share is 86%), and global forecast of total power generation installed capacity of renewable technologies on the right (CSP: Concentrated solar power) from 2016 to 2050* [16]**.**

According to [16] , PV applications will dominate the global growth of renewable-based electricity generation with more than 8500 GW of total installed capacity in 2050 as seen in figure 2.6. By this rapid escalation of renewables particularly PV technology in power production, the power system in the future may have a reduced share of conventional based power plants which have high and steady power generation capacity, and increased the share of the PV converter-based power plants which have intermittent power generation capacity and zero rotational masses. Thus, this huge penetration of PV power plants has a significant impact on the power system stability and security. The next section discusses the issues of the power system which arise due to the integration of large scale PV power plants.

# 3. IMPACT OF VAST PENETRATION OF PV POWER PLANTS ON POWER SYSTEM

As a non-traditional power generation facility which is mostly connected to the distribution network or close to the customer site, solar PV system can be regarded as distributed generation (DG) power plant [17,18]. Nowadays, governments urge energy companies to expand in distributed solar power generation with several motivations and incentives such as pollution reduction, energy efficiency and tax reduction. As a DG unit, PV power plants can support the distribution network positively by improving reliability, voltage support and energy efficiency [19]. For instance, by load management control systems, customers can decrease their electricity peak demands by shifting electricity use from peak periods to off peak periods. In this case, solar PV distributed generation unit with the demand response control can be deemed as a distributed energy resource. In contrast, the intermittency nature of PV power plants affects adversely not only the distribution network stability and power quality, but also the voltage and the frequency stability of the transmission network [20]. Conventional generators typically have the ability to sustain their active power output at constant production or change their power production corresponding to the load demand variation. PV power plant active power is mainly affected by the variability of solar irradiance. This variability of PV power plants has addressed several challenges which depend on the penetration level of PV power plants integrated into the power system. An overview for the impact of this large penetration level of PV power plants is discussed in the next sections.

## 3.1 Voltage regulation

Voltage quality at the distribution network feeder can be impacted adversely by irregular fluctuation nature of distributed PV power plant. The feeder voltage problems can be summarized as follows: voltage unbalance, voltage rise, and voltage flickers in the network. In classic traditional power system, the power flows from the higher voltage level at the medium voltage (MV) substation to the lower voltage level at the point of common connection (PCC) through tapping transformer until reaching to the customer loads. Therefore, the power flow can cause the voltage to drop at the customer levels which can be compensated using the transformer tap changers at certain levels. With high concentrations of the solar PV units connected to the distribution network, new direction of the power flow is introduced, and it may lead to a voltage rise at the distribution feeder.

However, voltage rise has substantial influence on the distribution feeder. Referring to [21], the voltage rise level is dependent on the solar PV contribution level in the low voltage (LV) network. The authors showed that, voltage rise level can be worsen as the PV power plants amount share increases. Thus, the solar irradiance changes rapidly due to the overpassing clouds as well as large number of PV active power output is injected into the LV network. As a result, the voltage at the distribution feeder increases remarkably and it is required to be mitigated. Additionally, voltage unbalance and voltage flicker effects are also rising on the distribution network. Voltage unbalance can cause serious damage in the customers electronic appliances. One percent of voltage unbalance can create 6 to 10 times of unbalanced currents that could degrade the motor windings and reduce the lifetime of induction loads [22]. Voltage flicker can cause malfunction of the lighting sources, electronic devices and uninterruptable power supply (UPS) systems. Thus, it is important to compensate these voltages technical disturbs due to integrating high amount of distributed PV facilities into the distribution network. Several methods have been used to compensate the voltage problems such as control of the distribution transformer on load tap changer (OLTC), battery energy storage systems (BESS) , static compensators units (STATCOM) and reactive power control [27–32]. For instance, in [32], the authors have proposed a reactive power control method based on PV inverter with voltage regulation. The authors in [28] have presented PV and STATCOM utilization method to improve system stability and perform voltage adaptation for solar PV farm at day and night time. The authors at [32,37] have showed different manners of using battery energy storage systems economically in voltage regulation. Thus, voltage regulation and voltage quality issues have to be mitigated due to the large contribution of PV power plants into the power grid.

## 3.2 Protection

As mentioned earlier, propagation of solar PV distributed units can invert the flow direction of the power at the feeder and substation levels. The contrary power flow direction can influence adversely on the network protection and coordination devices. This bidirectional power flow can be detected at the normal operation and during fault conditions as well. Typically, the protection coordination at the traditional classical network is based on the time and, or current grading from downstream at substation level to upstream in one direction into the loads. In this way, the overcurrent relays can operate as the closest upstream breaker seen from a fault will operate first and disconnect the smallest possible section of a line upon fault clearance. Adding more distributed generation units to the distribution network requires re-evaluation for the conventional relay coordination. According to several studies and research, solar PV as distributed generation unit can cause three major protection problems, sympathetic tripping, blinding effect and auto reclosing failures. The authors at [39,40] have introduced these protection risks due to PV integration in details and have offered different solutions. For example, sympathetic tripping means that the distributed PV unit can cause unnecessary tripping for an adjacent feeder when the fault occurred close to the MV substation. Blinding effect occurs when the fault at the end of the feeder and the solar DG unit provide the fault current with the major part so that the MV feeder relay will not trip and causes blinding. One significant proposed solution is the proper communication to coordinate between the protection relays.

## 3.3 Islanding and reliability

Islanding operation refers to the situation where distributed generation unit is located in the system to mitigate the frequency and voltage within the allowable regulations after the system is detached from the network utility. Islanding scenario can be divided into unintended islanding and intended islanding operation. Unintentional islanding for distributed power unit is often undesirable and not allowed in public distribution network for safety and security concerns. Thereby, the DG unit must be disconnected as fast as possible from the network. While, intentional islanding allows the DG unit to continue operation, but with specific critical control for frequency and voltage within the permissible limits enforced by the network operator. The responsibility for intended islanding mode relies on where the islanding is implemented. For instance, if the intended islanding mode is established at the public network then the grid company must assure the islanding operation regulations. Some of the islanding operation considerations have been proposed at [32]. Solar PV as distributed generation unit can lead to the same severe technical issues mentioned in case of islanding mode operation so that islanding should be quickly detected. According to [33], islanding mode can be sensed using remote or local technique manners. Remotely detection techniques are proposed based on the communication between the PV units and the grid utility such as supervisory control and data acquisition (SCADA) systems as discussed at [34,35]. By using advanced sensors, the islanding mode can be distinguished, and an event for the voltage and frequency current values should be sent to the central control room to show the current state of the system. Locally detection technique is dependent on the system measurements such as frequency, voltage, reactive and active power, total harmonic distortion

(THD) and state estimation as studied at [42–45]. These measurements values represent an indicator for the system status whether in normal or islanding operation. For example, at [44] and [46] , the measurement value of THD is used to monitor the islanding scenario as when islanding occurs, the THD levels increase due to PV inverter current injection which distorts the voltage response of the transformer. The authors at [45] and [47] have presented islanding detection tripping technique that can identify the rate of change of frequency (ROCOF) or rate of change of power (ROCOP) when they exceed the predetermined settings which are adjusted by ROCOF or ROCOP relays. On the other hand, correct placement of distributed PV facility may support the network to restore power supply to remote customers with intended islanding operation in case of fault outage. Therefore, islanding mode may improve network reliability by decreasing time and number of outages, but it affects the security of the network in case of unintended islanding occurs, so it requires stringent advanced protection system to maintain the network safety.

Network reliability can be analyzed and measured by SAIDI and SAIFI figures based on the fault frequency rate and number of outages. SAIDI and SAIFI stand for system average interruption duration index and system average interruption frequency duration index, respectively. Therefore, to enhance the network reliability, the number of outages and fault rate should be reduced. SAIDI impact can be figured based on where the islanding operation is implemented. Thus, placing PV distributed unit in the further location of the network at which high fault probability may happen, can provide the power to the customers in case of fault or planned maintenance outage. These islanding scenarios are beneficial especially when there is no back up connection from the network at remote or rural areas for certain customers. By comparing intentional islanding with traditional methods such as overhead lines or underground cables, to improve distribution network reliability, it is noted that intended islanding performs well both technically and economically [39]. In turn, synergy benefits can be obtained but with well-planned island and operation to keep efficient power quality.

## 3.4 Power quality

Supplying the power to customers with high efficiency and power quality is crucial for the distribution network operators (DSOs). According to IEC60038 and EN50160 standards, DSOs must comply with the minimum power quality requirements as voltage variation must not exceed 10% variation from the nominal voltage at the low voltage networks [40]. However, with high dispersion of intermittent PV power units into the distribution network, customers may experience voltage variations and adverse power quality due to the fluctuation in PV output. Adverse voltage quality disturbances may cause tripping or inadequate operation for the customer’s equipment and devices. Harmonics issues are also emphasized due to PV inverters which inject current and voltage harmonics into the distribution network as discussed at [41]. According to the author, the harmonic accumulation problem increases when many PV inverters connected to a certain feeder and thus, causes network losses. Several research studies have initiated and proposed solutions to mitigate the power quality problems [26,33] and [41–45]. At [26], one possible solution is proposed to lessen the voltage rise by coordination control between energy storage system with the transformer tap changer. Also, [45] has presented a robust control strategy to mitigate harmonic issues in the network by using inductor and capacitor filters. Therefore, power quality problems can be worsened with the quest of increasing the generated power from solar PV if appropriate proactive actions are not taken in the near future.

# 4. TECHNICAL GRID CODES REQUIREMENTS

In this chapter, the grid codes technical requirements, specifications and functions which are imposed by the relative transmission system operators (TSOs) globally are discussed for the connection of solar PV power plants into the power networks.

Traditional standards define the regulations of conventional synchronous generator-based power plants to boost network resiliency, strength and safety of distribution and transmission networks. Recently, a massive penetration of renewables-based power plants has contributed to the electricity production, especially solar PV and wind power technologies. Nowadays, solar PV and wind power represent an essential segment of the total power generation capacity in many countries such as Germany and Denmark [2]. As discussed earlier, the fluctuation caused by integrating huge number of renewables to the power system has a serious impact on the power system stability and power quality. Therefore, TSOs have recognized that it is no longer allowed to operate PV and wind based power plants independently. They must be complied with specific requirements and functions to contribute to the operation and stability of the power system. These supporting regulations and guidelines can be identified as connection grid codes. Grid codes specifications of the generation facility can measure the ability of the unit to withstand the power system fluctuations and disturbances such as voltage dips and swells, under and overfrequency disturbance. Also, it measures the capability of the generation unit to support the grid during and after sudden momentary disturbance event such as power system faults. This secures the grid and confirms efficient operation to participate in the wholesale markets. Grid codes in general can include connections codes, planning codes, operating codes and market codes but in this chapter, the connection grid codes technical requirements and guidelines are only investigated.

Two major turning events have occurred in the history of the connection grid codes that are linked to the massive contribution of renewable based power plants into the power system. The first event is the central European partial blackout in November 2006 that caused an interruption of the power supply for more than 15 million customers due to tripping of high voltage lines in northern Germany [46]. According to [46], the standard grid code requirement for wind power units was 49.5 Hz to withstand frequency disturbance. During this power disruption, a significant power imbalance experienced, and several wind power plant units were tripped when the frequency was dropped to 49 Hz. This less strict connection code for the wind plants have worsened the situation to recover the frequency stability faster as 40% of the total tripped units were wind generation units and leading into more load shedding in the European network. The second major event is so called 50.2 Hz problem in Germany which is mainly related to PV generators connected to the distribution network. PV technology is expanding abruptly and represents a substantial segment from the total generation capacity from German network. According to [47], PV power units were designed to shut down in case of frequency rise to 50.2 Hz according to the grid codes requirements. Thus, in case of surplus power in the grid, it could lead to a serious power disruption by disconnecting large number of PV units due to overfrequency which will deteriorate the situation to recover the frequency stability fast and pose a threat for the system stability. As a result, Germany has updated and modified the grid code regulations for PV and wind power plants according to the high level of penetration in their network.

Thus, these two significant learnt incidents as well as the impacts caused by integration of PV and wind power units have driven the TSOs in Europe and worldwide to update their connection grid codes by imposing new technical requirements and regulations. These technical requirements demand that PV power plants must have particular functions in their inverters in order to withstand the power system instability challenges. These functions are stipulated in the grid codes to fulfil the following objectives: assure reliable power supply for all consumers demands, ensure frequency and voltage operational boundaries to avert deterioration of other equipment connected to the grid, and ensure effective withstand ability against voltage and frequency sudden disturbances [47]. Therefore, in case of a new solar PV generation unit does not fulfill with the grid code connection regulations enforced in the country, the relevant grid operator shall reject the connection of this power generation unit. These regulations shall be applied to a new installed PV generation unit or even the existing PV facilities if their technical specifications are still not modified.

Globally, the compliance with the grid codes requirements are staggered according to different essential domains such as connection point voltage level, PV power plant size category and network system operator. For the network system operator domain, some countries stipulate different grid codes for their distribution system operator (DSO) or transmission system operator (TSO) based on at which network PV power plant is connected, whether to the distribution network or transmission network. The voltage level at the connection point and PV power plant size domains also vary from country to another and affect the grid codes requirements. For example, small size PV power plants are demanded to meet less stringent requirements than the large size PV power plants which are connected to transmission network. Also, in case of different voltage levels for distribution and transmission networks, it is demanded from PV power plants which are connected to transmission network to provide reactive power support in case of faults. Therefore, these three main domains are stipulated differently in each country's grid code according to network type and voltage levels. An example can be seen in table 1 from the Finnish grid code as the PV power plants are divided into categories of A, B, C and D which are connected at voltage level of less than or equal to 110 kV [48]. The same way is implemented in all other grid codes to categorize PV power plants according to their maximum rating capacity and at which voltage level at the connection point. Another example from Italian grid code which is classified PV power plants of category A in between 0.8 kW ≤ $P_n$ ≤ 11.08 kW, and category D is all PV power plants which are more than 10 MW at connection point voltage equal to 110 kV. In South Africa, grid codes are stipulated that category B is between 1 MVA and 20 MVA, while category D is equal or greater than 20 MVA.

***Table 1.*** *PV power plants classification categories based on rated capacity and connection point voltage imposed by Fingrid grid code* [48].

| Class category | Connection point voltage level | PV maximum rated capacity ($P_n$) range |
|---|---|---|
| **Class A** | Connection point voltage level is less than 110 kV | 0.8 kW ≤ $P_n$ <1 MW |
| **Class B** | Connection point voltage level is less than 110 kV | 1 MW ≤ $P_n$ <10 MW |
| **Class C** | Connection point voltage level is less than 110 kV | 10 MW ≤ $P_n$ <30 MW |
| **Class D** | Connection point voltage level is at least 110 kV | $P_n$ ≥ 30 MW |

In this thesis, only technical grid codes requirements and specifications are studied and analyzed to integrate medium and large scale PV power plants into the electrical network in global modern grid codes. The focus in this chapter is to identify the minimum modern grid codes requirements and functions which are demanded from PV power plants and also the future new requirements which are currently still under discussion. The global modern grid codes which are reviewed and studied in this thesis can be seen in table 2.

The grid codes, in this table, can be considered as the most recent code version of each country. The following sections are dedicated to compare and analyze the development of the recent requirements and specifications for PV power plants considering technical aspects during steady state and dynamic operation. These aspects include voltage and frequency nominal operating boundaries, fault ride through, reactive current support during voltage disturbance, voltage and reactive power control, frequency and active power control. The target of this comparison and study is to define the most recent minimum requirements and functions that must be supplemented with PV inverters to implement the same dynamic behavior of conventional generating facilities. The first section discusses the demanded behavior of PV power plants during the voltage and frequency deviations during steady state operation.

***Table 2.*** *International grid codes versions investigated in this thesis.*

| Grid code by country | System grid operator | Version |
|---|---|---|
| **Finland** | Fingrid | 2018 [48] |
| **European Network of Transmission System Operators for Electricity** | ENTSO-E | 2016 [49] |
| **Denmark** | Energinet.dk | 2016 [50] |
| **Germany** | VDE | 2018 [51] |
| **China** | NEA | 2012 [52,53] |
| **Spain** | REE | 2018 [54] |
| **Italy** | TERNA | 2018 [55,56] |
| **South Africa** | NERSA | 2019 [57] |
| **United States - Puerto Rico Electric Power Authority** | USA-PREPA | 2013 [58] |
| **Australia** | AEMO | 2019 [59] |
| **Malaysia** | Suruhanjaya Tenaga | 2017 [60] |
| **Egypt** | EETC | 2018 [61] |
| **Romania** | ANRE | 2013 [62] |
| **Japan** | JEAC | 2012 [63] |
| **Saudi Arabia** | SEC | 2018 [64] |

## 4.1 Voltage and frequency boundaries

Voltage and frequency operating ranges at the connection point are essential in all grid codes requirements to operate solar PV power plants within specified limits and time period during steady state operation. International global frequency is either 50 Hz or 60 Hz, and most of frequency nominal operating range is varying in between 47 to 52 Hz or 57 to 62 Hz. While, the voltage level at the connection point differs from country to another based on the network type and structure in the grid. For instance, the nominal voltage levels in Finnish grid are 110 kV, 220 kV and 400 kV and the normal fluctuation ranges are as follows: 105 – 123 kV, 215 – 245 kV and 395 – 420 kV respectively [48]. In Germany, the network nominal voltage levels are 110 kV, 220 kV and 380 kV and the normal fluctuation range are: 100 – 123 kV, 210 – 245 kV and 360 – 420 kV [51]. If the nominal connection voltage level can be considered as 1 pu then the operating range variation can be implemented by a certain percentage of this value. For example, in Finland, the normal fluctuation operating range for any voltage level is between 0.9 pu to 1.05 pu, while in Germany is between 0.9 pu to 1.10 pu. Malaysia imposes different operating ranges for different voltage levels variations at the connection point. It enforces a variation between 0.95 pu to 1.05 pu for 500 kV level while, the voltage below 275 kV and 132 kV should remain within 0.9 pu to 1.10 pu of the nominal voltage unless abnormal conditions prevail. So, the same way is implemented in all the grid codes according to each grid voltage levels and the specified nominal operating range by the relevant TSO. Therefore, the main challenge of the relevant TSO is to sustain the voltage and frequency operating ranges within the specified limits under which the PV power plants have to operate continuously or for a certain period of time. In this section, a comparison is drawn between the international grid codes for voltage and frequency nominal operating ranges and their impact on the minimum operation period of PV power plants. However, it is only mentioned that the voltage operating ranges of some voltage levels because there are various voltage levels that are implemented in each country. The requirements concerning the minimum time periods for which PV power plants have to be capable of operating on different voltages is specified only for class D power generating units in the ENTSO-E grid code [48]. Table 3 stipulates the minimum time periods which are demanded from solar PV power plants to be operating without disconnection from the network within different voltage levels between 20 kV to 500 kV in different regions globally. Also, table 4 illustrates the minimum time periods' specifications which are requested from PV power plants to stay connected at the PCC, but according to different frequency operating boundaries.

***Table 3.*** *Minimum operating time periods' requirements comparison for PV power plants within different voltage levels and boundaries imposed by international grid codes.*

| Synchronous region | Voltage level range at PCC (kV) | Voltage boundaries at PCC (pu) | Operation period (min) |
|---|---|---|---|
| **Europe** | 110 – 400 | 0.85 – 0.90 | 60 |
| | | 0.90 – 1.118 | Continuous |
| | | 1.118 – 1.15 | Initiated by relative TSO in between 20 ≤ time ≤ 60 |
| **Nordic** | 110 – 300 | 0.90 – 1.05 | Continues |
| | | 1.05 – 1.10 | 60 |
| | 300 – 400 | 1.05 – 1.10 | Initiated by relative TSO in time ≤ 60 |
| **Great Britain** | 110 – 300 | 0.90 – 1.10 | Continuous |
| | 300 – 400 | 1.05 – 1.10 | 15 |
| **Ireland and Northern Ireland** | 110 – 300 | 0.90 – 1.118 | Continuous |
| | 300 – 400 | 0.90 – 1.05 | Continuous |
| **Baltic** | 110 – 300 | 0.85 – 0.90 | 30 |
| | | 0.90 – 1.118 | Continuous |
| | | 1.118 – 1.15 | 20 |
| | 300 – 400 | 0.88 – 0.90 | 20 |
| | | 0.90 – 1.097 | Continuous |
| | | 1.097 – 1.15 | 20 |
| **Malaysia** | 275 – 500 | 0.90 – 1.05 | Continuous |
| | | 1.05 – 1.10 | 15 |
| | 132 – 275 | 0.90 – 1.10 | Continuous |
| | < 132 | 0.94 – 1.06 | Continuous |
| **China** | ≥ 35 | 0.90 – 1.10 | Continuous |
| | < 20 | 0.93 – 1.07 | Continuous |
| **Egypt** | 11 – 132 | 0.85 – 0.90 | 30 |
| | | 0.90 – 1.10 | Continuous |
| | | 1.10 – 1.15 | 30 |
| **Saudi Arabia** | 110 – 380 | 0.90 – 0.95 | 30 |
| | | 0.95 – 1.05 | Continuous |
| | | 1.05 – 1.10 | 30 |

***Table 4.*** *Minimum operating time periods' requirements comparison for PV power plants within different frequency operating boundaries imposed by international grid codes.*

| **Grid code by country** | **Frequency (Hz)** | **Frequency boundaries (Hz)** | **Maximum operating time period** |
|---|---|---|---|
| **Germany** | 50 | $f > 51.5$ | Trip instantly |
| | | $47.5 < f < 51.5$ | Operate continuously |
| | | $f < 47.5$ | Trip instantly |
| **Spain** | 50 | $f > 51.5$ | Trip instantly |
| | | $47.5 < f < 51.5$ | Operate continuously |
| | | $48 < f < 47.5$ | 3 s |
| | | $f < 47.5$ | Trip instantly |
| **China** | 50 | $f > 50.2$ | 2 min |
| | | $49.5 < f < 50.2$ | Operate continuously |
| | | $48 < f < 49.5$ | 10 min |
| | | $f < 48$ | Depend on inverter curve |
| **USA-PREPA** | 60 | $f > 62.5$ | Trip instantly |
| | | $61.5 < f < 62.5$ | 30 s |
| | | $57.5 < f < 61.5$ | Operate continuously |
| | | $56.5 < f < 57.5$ | 10 s |
| | | $f < 56.5$ | Trip Instantly |
| **Saudi Arabia** | 60 | $f > 62.5$ | Trip instantly |
| | | $61.6 < f < 62.5$ | 30 s |
| | | $60.6 < f < 61.5$ | 30 min |
| | | $57.8 < f < 60.5$ | Operate continuously |
| | | $57.5 < f < 58.7$ | 30 min |
| | | $57 < f < 57.4$ | 30 s |
| | | $f < 57$ | Trip instantly |
| **Finland** | 50 | $f > 51.5$ | Trip instantly |
| | | $51 < f < 51.5$ | 30 min |
| | | $49 < f < 51$ | Operate continuously |
| | | $47.5 < f < 49$ | 30 min |
| | | $f < 47.5$ | Trip instantly |
| **Japan** | 50 East | $f > 51.5$ | Trip instantly |
| | | $47.5 < f < 51.5$ | Operate continuously |
| | | $f < 47.5$ | Trip instantly |
| | 60 West | $f > 61.8$ | Trip instantly |
| | | $58 < f < 61.8$ | Operate continuously |
| | | $f < 58$ | Trip instantly |
| **Egypt** | 50 | $f > 51.5$ | Trip instantly |
| | | $47.5 < f < 51.5$ | Operate continuously |
| | | $f < 47.5$ | Trip instantly |
| **South Africa** | 50 | $f > 52$ | 4 s |
| | | $51 < f < 52$ | 60 s |
| | | $49 < f < 51$ | Operate continuously |
| | | $48 < f < 49$ | 60 s |
| | | $47 < f < 48$ | 10 s |
| | | $f < 47$ | 0.2 s |

| | | | |
|---|---|---|---|
| **Italy** | 50 | $f > 52$ | Trip instantly |
| | | $51.5 < f < 52$ | 30 min |
| | | $47.5 < f < 51.5$ | Operate continuously |
| | | $47 < f < 47.5$ | 60 s |
| | | $46.5 < f < 47$ | Fraction of second |
| | | $f < 47$ | Trip instantly |
| **Denmark** | 50 | $f > 52$ | Trip instantly |
| | | $47 < f < 52$ | Operate continuously |
| | | $f < 47$ | Trip instantly |
| **Australia** | 50 | $f > 52$ | 2 s |
| | | $47.5 < f < 52$ | Operate continuously |
| | | $f < 47.5$ | 2 s |
| **Malaysia** | 50 | $f > 52$ | Trip instantly |
| | | $47.5 < f < 52$ | Operate continuously |
| | | $f < 47.5$ | Trip instantly |
| **Romania** | 50 | $f > 52$ | Trip instantly |
| | | $47.5 < f < 52$ | Operate continuously |
| | | $f < 47.5$ | Trip instantly |

Most of grid codes are merging the time period requirements for both voltage and frequency boundaries at which the PV power plant shall have the ability to operate continuously or for a certain period of time. An example from the Nordic synchronous area is Finland which imposes these specified requirements and boundaries as seen in figure 4.1 for all voltage levels. It is noticed that from the figure that the PV power plant can operate continuously when the voltage variates between 0.9 pu to 1.05 pu and in the same time the frequency variates between 49 Hz and 51 Hz. However, PV power plant is allowed to curtail its active power output if the frequency is decreased up to 47.5 Hz within maximum period of 30 minutes. In case the frequency differs between 50 Hz and up to 51.5 Hz, the PV power unit has to be connected and operate only for 30 minutes. When the voltage fluctuates over 1.05 pu and up to 1.10 pu, the PV power plant has to stay connected and operate for maximum 60 minutes. The same way is enforced by other grid codes but within different frequency and voltage operating ranges, and different voltage levels such as Germany, Denmark and South Africa. Therefore, PV power plants must have the ability to operate within these several voltage levels, fluctuation ranges and withstand sudden voltage disturbances such as over or undervoltage. All grid codes have imposed certain requirements and specifications for solar PV power units to withstand the short time voltage and frequency disturbance during faults. The following section illustrates a comparison between these requirements during a sudden voltage disturbance in the international grid codes.

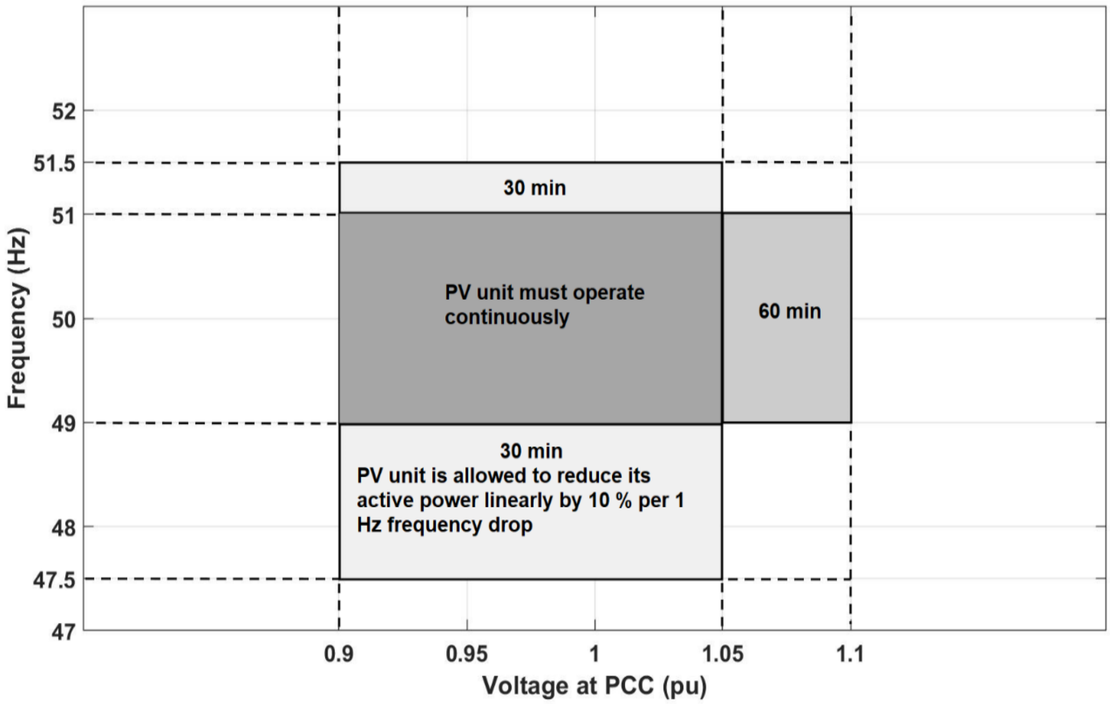


***Figure 4.1.*** *Minimum operating time periods' requirements for PV power plants within different frequency and voltage boundaries imposed by Fingrid grid code* [48].

## 4.2 Fault ride through

Fault ride through (FRT) capability is the ability of DG unit to withstand fault disturbance at the connection point and continue to operate during and after the disturbance for a certain period. Solar PV distributed generation units were initially considered to have merely a marginal effect on power system. Thus, TSOs had less stringent requirements for PV integration to their networks. However, as the share of PV units kept increasing, it was later discovered that faults in the transmission system could lead to huge amount of tripping of PV power plants if too sensitive protection settings were implemented [46]. In order to avert these sorts of issues, TSOs have started to stipulate additional strict connection requirements for PV power plants. For example, frequency and voltage protection settings were demanded to be less sensitive for avoiding tripping of PV power plants during frequency and voltage disturbances. Therefore, grid codes have been driven to demand FRT capability from PV units, which specifies how deep and longlasting voltage dips generating units need to be capable of riding through without losing their stability. The code provides certain specifications which explain when the PV power plants must stay connected to the grid during and after the fault. Also, some of the TSOs have also started to demand from PV power plants to inject or absorb reactive current to support the grid during voltage rises or falls to maintain system stability. FRT capability can be divided into low voltage ride through (LVRT) and high voltage ride through (HVRT) functions according to the specific grid code requirements. Faults in the power system can be considered as symmetrical or asymmetrical faults, however each local TSO can specify in detail what kind of LVRT or HVRT function is required in their networks based on the fault type. For example, ENTSO-E states that PV generating units are demanded to have the ability for riding through voltage dips during symmetrical faults and the phase to phase voltage remains over the LVRT curve without losing their stability [49]. While, in case of asymmetrical faults, there is no requirement assigned by ENTSO-E for FRT. It is only mentioned that these requirements shall be related to the relative TSO responsibility. The next sections illustrate analysis and comparison between the global international grid codes for LVRT and HVRT enforced by the relevant TSO during voltage dips or swells.

### 4.2.1 Low voltage ride through

Low voltage ride through (LVRT) requirement is one of the significant specifications which has stipulated in all modern grid codes due to the high penetration of PV power plants into the power system. LVRT requires that the PV power unit has to act as conventional power plant by staying linked to the grid during faults to ensure voltage stability. The general idea of LVRT requirement when the PV unit is connected to the connection point can be seen in figure 4.2. PV power unit should withstand the voltage dip and remain in operation during a specified period from $t_0$ to $t_1$ when the voltage fall occurs at instant $t_0$ and causes a voltage decrease at the PCC from nominal voltage $V_n$ to $V_0$. After the fault is cleared at $t_1$, the PV power unit should quickly recover its operation and remain connected until it stabilizes the voltage again to a value of $V_1$ during a period between $t_1$ to $t_2$. Otherwise, it must be disconnected, and tripping is allowed. So, at area A, the PV generation unit can operate normally as the voltage profile is still between the nominal operation range at the PCC. When the voltage at area B, the PV power unit must continue operating and withstand the voltage dip for a period until the voltage returns to its nominal value at $V_1$. If the voltage is at area C, the PV unit can be detached from grid and tripping is allowed. The values and grid code specifications of $t_0$, $t_1$, $t_2$, $V_0$ and $V_1$ can differ from country to another.

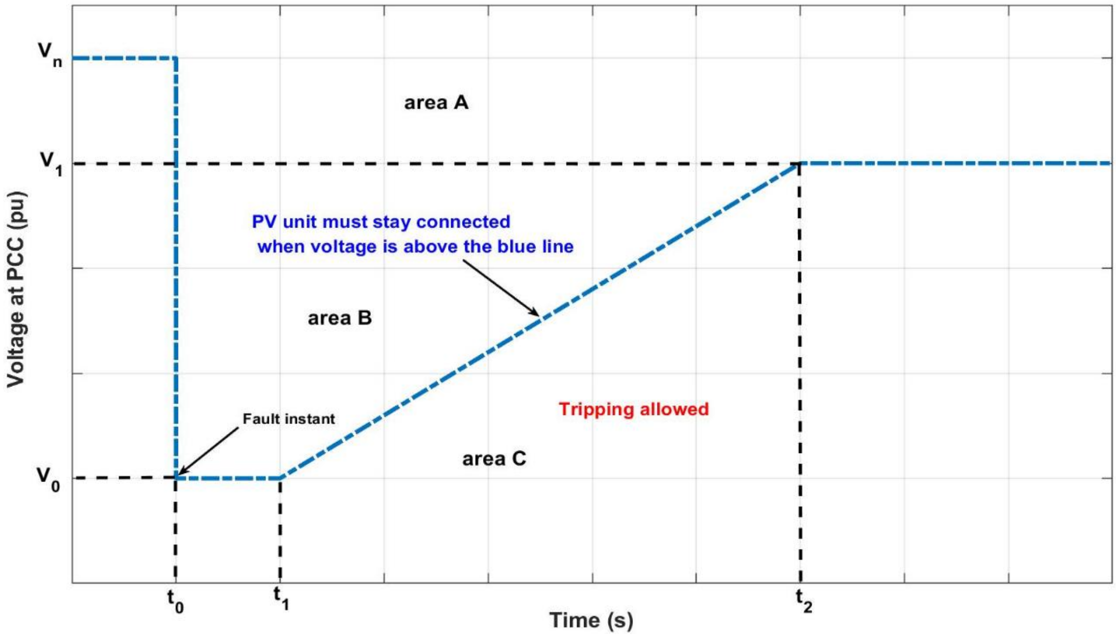


***Figure 4.2.*** *LVRT requirement typical curve of PV power plant during and after a momentary voltage dip at the PCC.*

For instance, in Finland, Fingrid TSO imposed the FRT guidelines for symmetrical and asymmetrical faults as seen in figure 4.3 [48]. When fault occurs, the LVRT requirement demands that PV power unit has to stay operating for 0.15 s when the voltage dropped momentary to 95% of the nominal voltage.

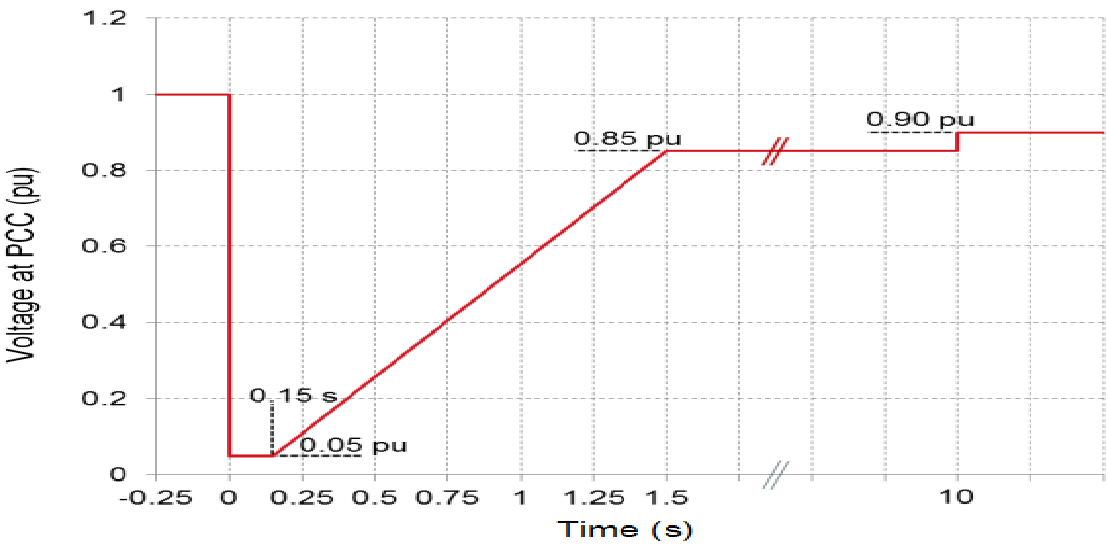


***Figure 4.3.*** *LVRT requirement for PV power plants during and after momentary undervoltage disturbance imposed by Fingrid grid code* [48].

After the fault is cleared, the solar PV has to stay operating until the voltage rise to 0.85 pu during 1.35 s and continue operating until the voltage becomes 0.9 pu of the nominal voltage. A detailed comparison of LVRT specifications and requirements for PV power units in different grid codes globally is implemented in table 5. The requirements include the voltage and time period specification during the voltage dip for $t_0$, $t_1$, $t_2$, $V_0$ and $V_1$. When fault occurs, Italy, Malaysia and South Africa have stipulated that the PV unit should withstand 100% of voltage fall and remain connected to the system until 0.15 seconds. Australia, Egypt and Saudi Arabia have also enforced the same 100% of voltage fall withstand capability, but within longer time periods of 0.45, 0.25, 0.30 seconds respectively.

When the voltage falls to zero at the former grid codes, it can be considered as a special case of the LVRT and it can be called as zero voltage ride through (ZVRT). ZVRT can be considered as an excessive case as the voltage is dropped to zero however, tripping of the PV unit is not allowed. In Finland, Fingrid TSO has imposed different time periods and voltage dip requirements according to the PV size category. It is stipulated that PV power unit of category C has to resist a voltage drop of 0.05 pu and continue operation for 0.15 seconds while PV power plant of category D has to mitigate 0.0 pu voltage drop within 0.20 seconds. Denmark grid codes stipulates that the PV power unit has to resist a voltage decrease of 0.90 pu and operate continuously for 0.25 seconds. When the voltage falls to 0.15 pu, Romania and USA-PREPA have imposed that PV have to resist the same value of voltage drop but within different time periods. However, Germany has specified the same voltage drop but within different time period of 0.15 and 0.22 seconds based on the type of fault. Japan, Spain and China have imposed the least stringent requirement for the voltage dip of 0.20 pu, but for a slightly longer period of time.

After the fault is cleared, grid codes enforce that the PV unit must stay running for a certain period of time till the voltage is restored to a certain value as well. From table 3, the voltage has to be restored between 0.80 pu to 0.90 pu after the fault is cleared within different time settings except only Germany which requires the voltage to be restored to 0.75 pu in case of two-phase fault. The grid codes in Japan, Australia and Spain are demanded to restore the voltage up to 0.80 pu of the nominal voltage while, Denmark, Finland, South Africa and USA-PREPA require to restore the voltage up to 0.85 pu within various periods of time. Germany has imposed the same value of voltage restoration for 3 seconds but only in case of symmetrical three-phase fault. In case of voltage recovery to 0.90 pu of the nominal voltage, the PV unit has to remain connected of a time setting at 2, 3 and 1.5 seconds in China, Malaysia and Romania.

***Table 5.*** *LVRT requirement comparison for PV power plants during and after undervoltage disturbance at the PCC imposed by international grid codes.*

| | During fault | | After fault | |
|---|---|---|---|---|
| **Grid code by country** | $V_0$ (pu) | $t_1$ (s) | $V_1$ (pu) | $t_2$ (s) |
| **Australia** | 0 | 0.45 | 0.80 | 0.45 |
| **Malaysia** | 0 | 0.15 | 0.90 | 1.50 |
| **South Africa** | 0 | 0.15 | 0.85 | 2.0 |
| **Italy** | 0 | 0.15 | 0.20 & 0.75 & 0.8 | 0.50 & 0.90 & 20 |
| **Finland (D)** | 0 | 0.20 | 0.85 | 1.50 |
| **Egypt** | 0 | 0.25 | 0.40 & 0.90 | 1.0 & 3.0 |
| **Saudi Arabia** | 0 | 0.30 | 0.80 & 0.90 | 1.30 |
| **Finland (C)** | 0.05 | 0.15 | 0.85 | 1.50 |
| **Denmark** | 0.10 | 0.25 | 0.85 | 1.50 |
| **Romania** | 0.15 | 0.625 | 0.90 | 3.0 |
| **Germany (3 – phase fault)** | 0.15 | 0.15 | 0.85 | 3.0 |
| **Germany (2 – phase fault)** | 0.15 | 0.22 | 0.75 | 3.0 |
| **USA-PREPA** | 0.15 | 0.60 | 0.85 | 3.0 |
| **Spain** | 0.20 | 0.50 | 0.80 | 1.0 |
| **Japan** | 0.20 | 1.0 | 0.80 | 1.20 |
| **China** | 0.20 | 0.625 | 0.90 | 2.0 |

Some of the grid codes require to recover the voltage gradually within different periods of time such as Italy, Egypt and Saudi Arabia. For example, Egyptian grid code requires that the PV power plant has to recover 40% of the voltage firstly in 1 second, and then restore it to 90% of the nominal voltage in 3 seconds. A comparison chart is established between the international grid codes for LVRT requirements in figure 4.4. The stringent requirement of LVRT can be analyzed from all the grid codes which are imposed ZVRT capability within different time settings. However, the most stringent requirement is observed by Australian grid code because it is demanding that the PV power unit must withstand a voltage drop of 0 pu and restore it up to 0.8 pu in the same time setting of 0.4 seconds. The least stringent requirement has been imposed by USA-PREPA because PV unit can take longer time of 3 seconds to recover 85% of the voltage when the voltage drops to 0.15 pu.

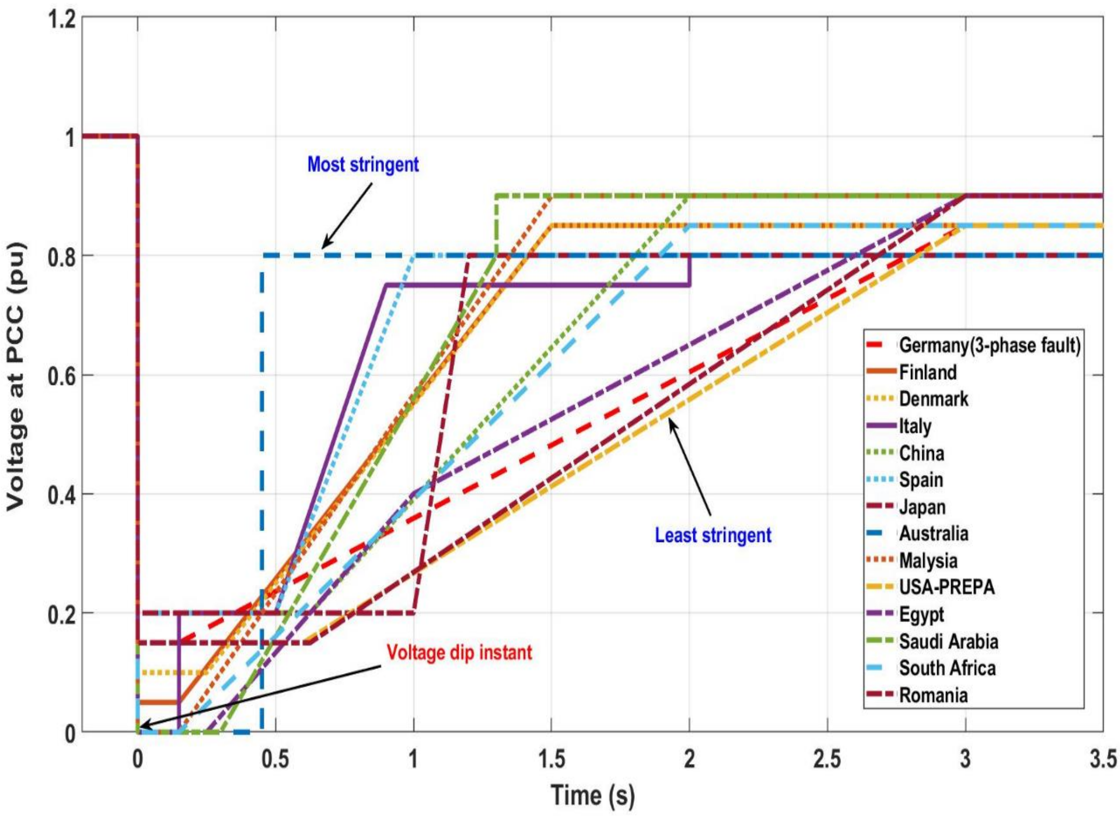


***Figure 4.4.*** *LVRT requirement chart comparison for PV power plants during and after undervoltage disturbance imposed by international grid codes.*

## 4.2.2 High voltage ride through

To keep the overall voltage stability in the grid, PV power plants may be required to withstand not only the voltage dip event by LVRT capability, but also to stay connected to the PCC against voltage rise event with high voltage ride through (HVRT) function. The voltage swell can lead to overvoltage problems in the grid so that several grid code operators in different countries recently have imposed HVRT specifications regardless of the low probability of overvoltage events rather than the undervoltage. The typical idea of HVRT requirement during voltage rise at the PCC can be seen in figure 4.5. It is observed that the PV unit is operating normally when the voltage at PCC is nominal at $V_n$. When a voltage rise is occurred at instant $t_r$, the voltage is swelled to a certain value at $V_r$ and remained at this value for a certain period of time until $t_1$.

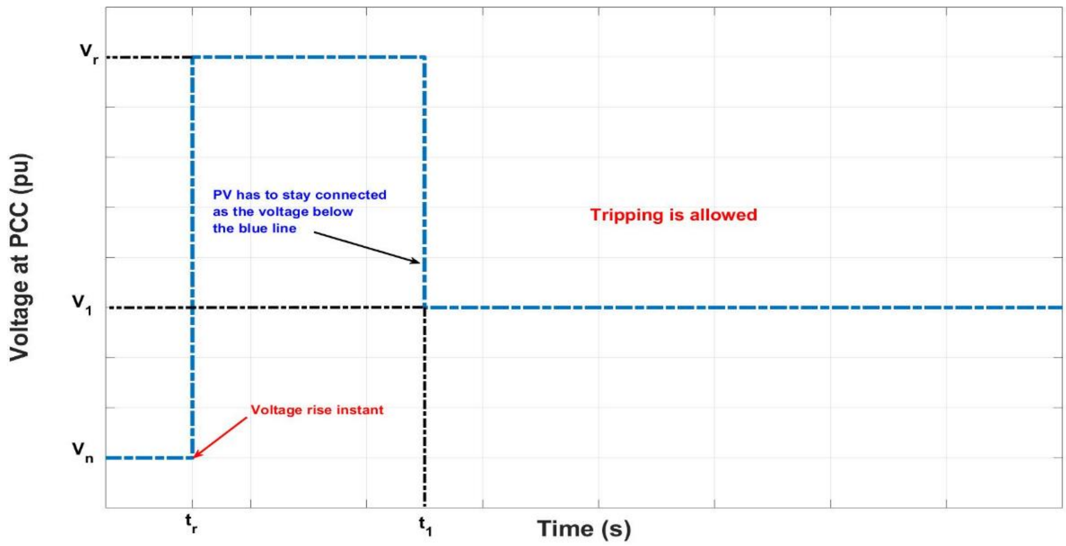


***Figure 4.5.*** *HVRT requirement typical curve for PV power plant during and after a momentary voltage swell at the PCC.*

During this period of time from $t_r$ to $t_1$, solar PV unit must mitigate the voltage rise $V_r$ and continue operation without tripping until the overvoltage is cleared at $t_1$. After the voltage swell is cleared, the PV power plant has to recover the voltage to at least the admissible voltage value at $V_1$. Therefore, the PV power plant must operate continuously as long as the voltage is below the blue line otherwise, tripping is allowed. The specifications for $V_n$, $V_1$, $V_r$ and $t_1$ vary from country to another according to each grid code requirements. A chart comparison of HVRT requirement in different grid codes globally is implemented in figure 4.6 and a detailed comparison is implemented in table 6 for its specifications.

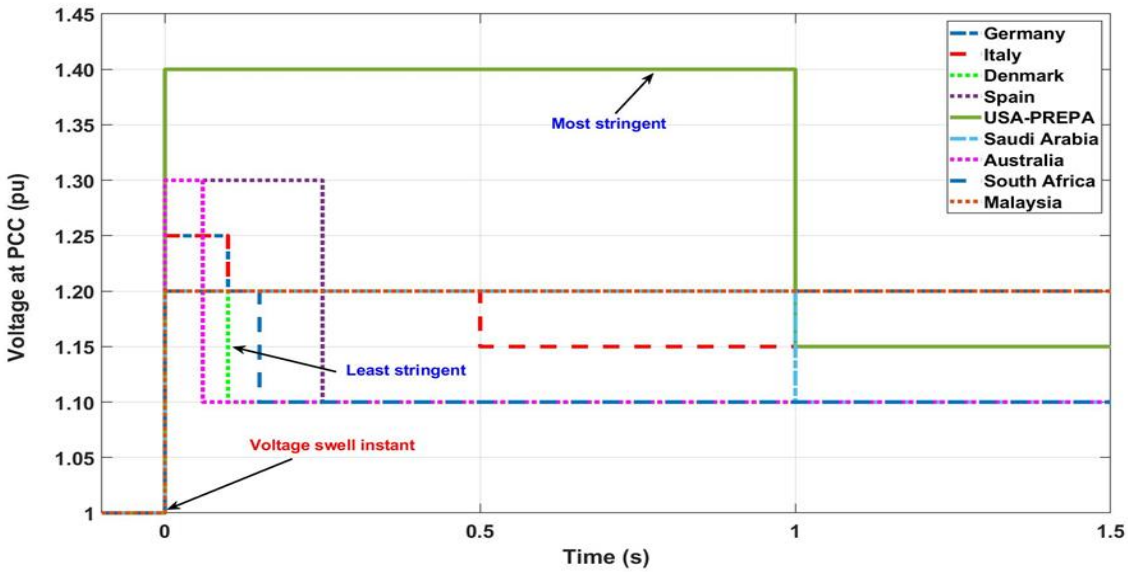


***Figure 4.6.*** *HVRT requirement chart comparison for PV power plants during and after an overvoltage at the PCC imposed by international grid codes.*

As per the comparison, the most stringent requirement is enforced by the USA-PREPA grid operator as it is demanded that the PV power plant has to endure 140% of a voltage swell and remain into operation under this overvoltage value for a time setting of 1 second until the voltage returns to an admissible value at 1.15 pu. These voltage and time requirements can be considered as the highest overvoltage resist capability within the longest time period. Spain and Australia have also enforced quite strict regulations for an overvoltage of 1.30 pu, but the solar PV unit has to stay connected and endure this voltage rise for a shorter period of time of 0.25 and 0.06 seconds. German and Italian grid codes have been imposed a gradual time setting to withstand an overvoltage of 1.25 pu as the PV unit shall firstly restore the voltage to 1.20 pu and then to the nominal admissible value at 1.15 pu withing two steps of time periods as seen in table 6.

Denmark and South Africa enforce the same requirements during a voltage rise of 1.20 pu and demand that the PV power plant has to restore the voltage at 110% from the nominal value within 0.10 and 0.15 seconds. Malaysia can be considered as a special case because it requires that the PV power plant has to stay in continuous operation even in case of a voltage rise of 120% of the nominal voltage. As mentioned earlier, the overvoltage events are less frequent to occur in the power grid compared to the undervoltage so that some countries have not imposed any requirements for the HVRT capability for PV power plants integration such as China, Japan, Finland, Romania and Egypt.

***Table 6.*** *HVRT requirement comparison of PV power plants during and after overvoltage disturbance imposed by international grid codes (NS*: Not stipulated at the grid code regulations).*

| | During and after voltage rise | | |
|---|---|---|---|
| **Grid code by country** | $V_r$ (pu) | $t_r$ (s) | $V_1$ (pu) |
| **USA-PREPA** | 1.40 | 1.0 | 1.15 |
| **Australia** | 1.30 | 0.06 | 1.10 |
| **Spain** | 1.30 | 0.25 | 1.10 |
| **Germany** | 1.25 | 0.10 & 5.0 | 1.20 & 1.15 |
| **Italy** | 1.25 | 0.10 & 0.50 | 1.20 & 1.15 |
| **Saudi Arabia** | 1.20 | 1.0 | 1.10 |
| **Denmark** | 1.20 | 0.10 | 1.10 |
| **South Africa** | 1.20 | 0.15 | 1.10 |
| **Malaysia** | 1.20 | Continuous | 1.20 |
| **Egypt** | NS* | NS | NS |
| **Japan** | NS | NS | NS |
| **China** | NS | NS | NS |
| **Finland** | NS | NS | NS |
| **Romania** | NS | NS | NS |

As per the previous analysis and comparison, the LVRT function can be regarded as a compulsory function for PV power plants integration, while HVRT function is still not an obligatory function in several global grid codes. It can be also observed that the PV unit must have the ability to support the voltage stability at the PCC during and after voltage dips and swells, so that PV inverters must have the capability to provide a reactive power support during and after the undervoltage or overvoltage faults to maintain the voltage again to the permissible operating limits after the fault is cleared. For instance, to restore the voltage to the admissible values $V_1$ as mentioned for LVRT or HVRT specifications then the PV inverter must inject or absorb reactive current into the grid after the fault is cleared. Therefore, most of recent grid codes are imposed the reactive current support function to be supplemented to the PV inverter within certain values and settings. The following section illustrates these different specifications which are required by different grid codes.

## 4.3 Reactive current support

The reactive current support (RCS) function is based on the fact that the voltage variation can be assisted with reactive power support by injecting or absorbing reactive current by the PV inverter during voltage dips or swells. Grid system operators shall assure that PV power units have the ability to support the grid during voltage disturbances by initiating an extra of reactive current support function. Most of the grid operators demand that the PV unit has to activate the RCS capability during LVRT and HVRT requirement to stabilize the voltage within the permissible operating limits after voltage dip or swell. The amount of reactive current injection or absorption depends on the value of voltage dip or swell, dead bands for voltage normal operation and the control response time to activate the reactive current function. The basic idea of RCS requirement function can be seen in figure 4.7. During normal operation between the voltage dead band of $\pm V\%$, the PV power unit has to perform normally with zero reactive current support. If the voltage starts to rise or fall outside the dead band limits, the control system requests the reactive current absorption or injection activation from PV inverter to fulfill the slope $k$ (droop) value into the red line. The red line behavior can take any other shape based on the requirements enforced by each country grid codes.

In case the voltage disturbance is outside the dead band boundaries, the RCS function requests the PV inverter to inject or absorb reactive current of $\Delta I_q\%$ corresponding to the voltage change of $\Delta V\%$. The maximum amount of injection or absorption of reactive current can be implemented when the voltage disturbance reaches to $V_{min}$ or $V_{max}$ percentage. For instance, from figure 4.7, the maximum reactive current injection during undervoltage fault can be expressed from the following expression:

$$I_q \geq k\ (1 - V_{min)} \qquad (1)$$

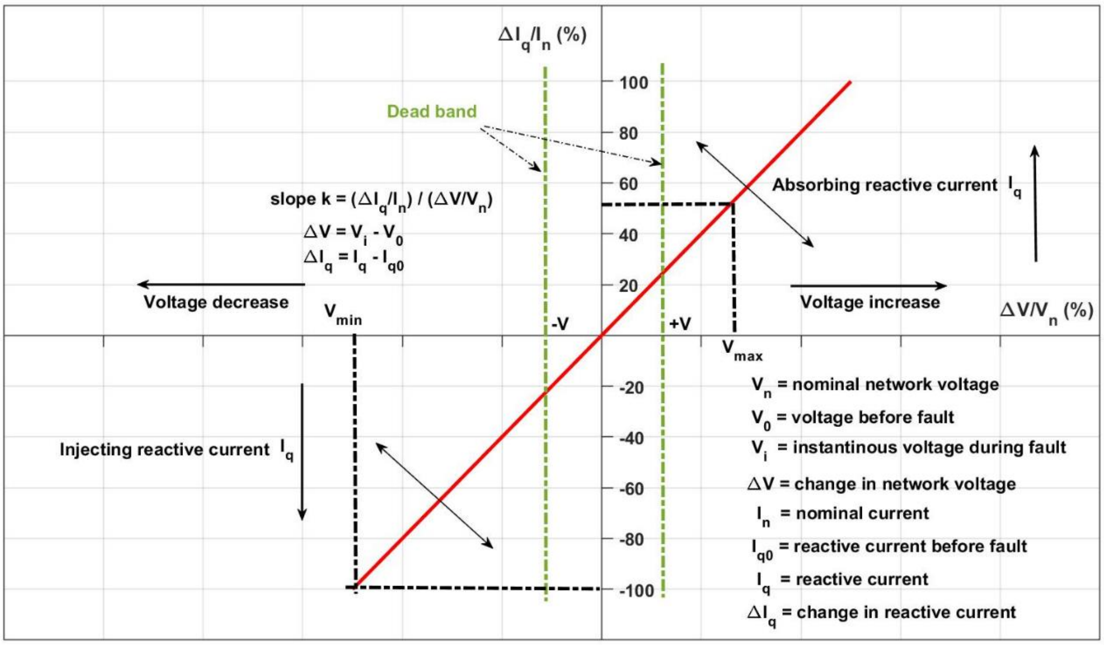


***Figure 4.7.*** *RCS requirement typical curve of PV power plant unit during voltage dip or swell at the PCC.*

The specifications of the dead band limits ±*V*%, $V_{min}$%, $V_{max}$% and droop *k* vary according to each country grid code. A chart comparison of reactive current support requirements is implemented in figure 4.8 which is specified by several TSOs in different countries. The grid codes in Germany enforces a voltage dead band of normal operation of ±10% for the solar PV unit so, the voltage can variate normally between 0.90 pu and 1.10 pu, and the reactive current support in this case equals zero. In case the voltage falls or rises by 1%, it is required to initiate 2% of reactive current injection or absorption which means that the droop *k* in this case equals 2% (blue line). The maximum reactive current injection of 100% has to be initiated when the voltage is equal to or less than 50% of the nominal value. The same droop is imposed by Egyptian grid code but the maximum reactive current injection of 100% can be achieved when the voltage is decreased by 40 %. Chinese grid operator imposes reactive current assistance by 105% of rated current when the voltage drops lower or equals to 80% from the nominal voltage.

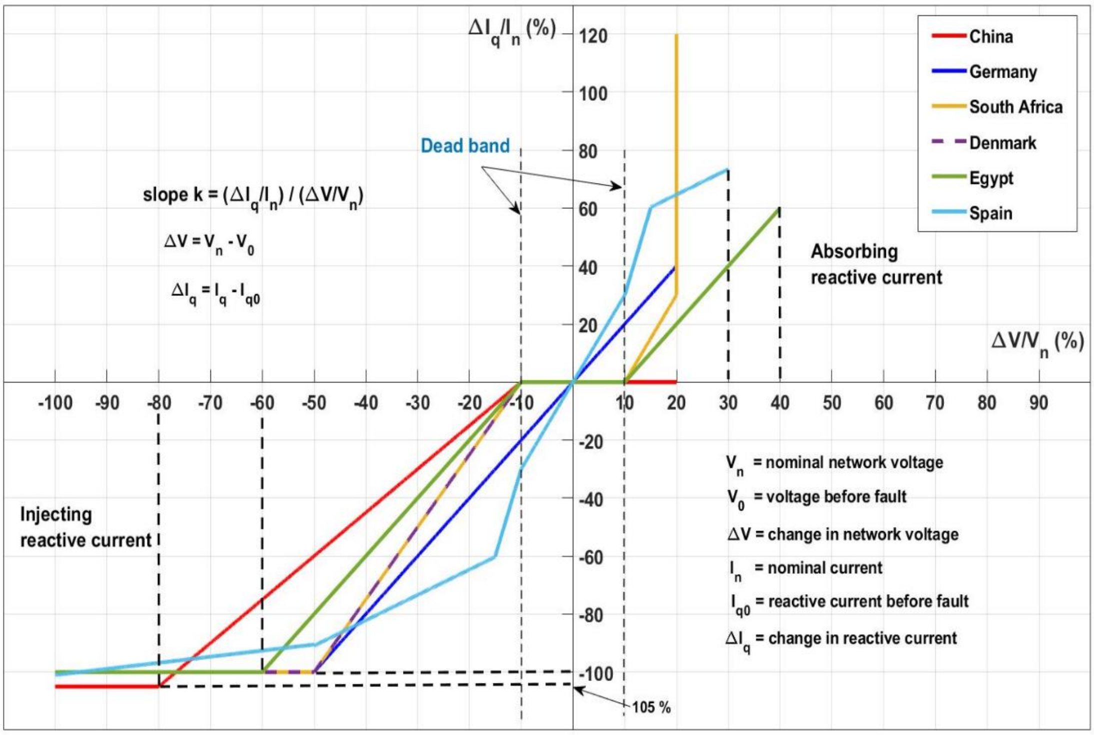


***Figure 4.8.*** *RCS requirement comparison for solar PV power plants during voltage disturbance imposed by different international grid codes.*

While, if the voltage falls between 0.20 pu to 0.90 pu, it is demanded from PV power unit to inject a reactive current with a slope of *k* = 1.5% to restore the voltage within the dead band limit. This grid code does not permit reactive current absorption in case of voltage swell more than the dead band. South Africa and Denmark have imposed the same requirements of *k* = 2.5% slope when the voltage in between 0.50 pu to 0.90 pu, and it is demanded to deliver 1 pu of reactive current when the voltage is equal or lower than 0.50 pu. South Africa demands also reactive current absorption when the voltage is swelled between 1.10 pu to 1.20 pu while, Denmark does not impose any reactive current absorption capability in case of voltage rise. A comparison for the specifications of the reactive current support in the international grid codes is drawn in table 7.

The maximum restoration time to stabilize the voltage within the dead band range for Denmark and South Africa is 100 ms and 60 ms. Spanish TSO imposes a variable droop between 2% to 6% (green line) for both reactive current injection and absorption in case of the voltage exceeds the dead band range of ±10% within a maximum restoration time of 30 ms. USA-PREPA mandates also a variable slope from 1% to 5% for the reactive current support function if the voltage exceeds its dead band range from 0.85 pu to 1.15 pu.

***Table 7.*** *RCS requirement comparison for PV power plants during voltage disturbance imposed by international grid codes (NS*: Not stipulated in the grid code regulations).*

| Grid code by country | Voltage dead band | Droop slope | Type of faults | Restoration time |
|---|---|---|---|---|
| | ±*V* (%) | *k* (%) | | t (ms) |
| **Germany** | ±10 | 2 | Symmetrical and asymmetrical | < 20 |
| **China** | ±20 | 1.5 | Symmetrical and asymmetrical | NS* |
| **Spain** | ±10 | Variable 2 - 6 | Symmetrical and asymmetrical | < 30 |
| **Denmark** | ±20 | 2.5 | Symmetrical and asymmetrical | < 100 |
| **South Africa** | ±20 | 2.5 | Symmetrical and asymmetrical | < 60 |
| **USA-PREPA** | ±15 | Variable 1 to 5 | Symmetrical and asymmetrical | NS |
| **Saudi Arabia** | ±5 | 2 | Symmetrical only | 60 |
| **Finland** | ±10 | 2.5 | Symmetrical and asymmetrical | 30 to 50 |
| **Egypt** | ±10 | 2 | Symmetrical only | 10 |
| **Malaysia** | ±10 | Max. reactive current | Symmetrical and asymmetrical | NS |
| **Australia** | ±10 | 4 for voltage dip<br>6 for voltage rise | Symmetrical and asymmetrical | < 70 |

Some grid codes such as Malaysia is demanded from PV power unit to inject the maximum reactive current in case of the voltage is lower than 0.90 pu to restore the voltage within the dead band range at the PCC. But this maximum reactive current should not exceed the transient rated current of the PV power unit. In some cases, injecting maximum reactive current may lead to opposite effect and voltage instability in PV feeder, thus it is recommended to implement droop control in order to avoid these probable instabilities. All of the grid codes have imposed the reactive current support capability for symmetrical and asymmetrical faults except Egypt and Saudi Arabia have imposed this function only for symmetrical three-phase fault. Both are stipulated that it is not permissible to activate the reactive current injection to avoid escalating of the voltage outside of the dead band. Some other grid codes such as Romania and Italy are not clarified the reactive current support slope or specifications when fault occurs.

It can be noted from the comparison and analysis that the RCS function is essential requirement in most of the grid codes. It is mostly imposed during voltage dip to inject reactive current when the PV power plant activates the LVRT capability to restore the voltage within the dead band limits. Few grid codes have requested to activate the RCS function during voltage rise for HVRT requirement. The recommended droop range variates in all of the grid codes between 1% to 6% during voltage dip or swell. Therefore, the RCS injection function can be considered as a minimum technical requirement with LVRT in all of the grid codes while, the RCS absorption function can be considered as a future requirement in case of HVRT, and it is expected to be stipulated by most of the grid codes in the near future.

## 4.4 Voltage and reactive power control

Voltage control during steady state operation is intended for regulating the voltages during normal operating conditions if voltage fluctuates gently within the specified variation limits. Typical dynamic voltage control requirements are such that the operation of the voltage controller should not be disturbed by voltage or frequency variations, or by momentary voltage disturbance. Also, it has to consider the impact of the voltage controller on power system dynamics during tuning the controller with intermittent resource like solar PV power units [48]. Voltage control with vast contribution of PV power plants into the grid confronts two major control challenges [5]. The first challenge is how the generation unit can maintain the voltage within the boundaries specified by the local TSO. The second challenge is that the PV power plants have to fulfil the requirements issued by the relevant grid operator for active and reactive power control boundaries. According to

[49,65], the voltage control in PV power plants can be implemented by several methods such as voltage regulation control, power factor control or reactive power control. The voltage regulation control mode relies on a droop function of the voltage variation corresponding to reactive power variation. Power factor control mode regulates the voltage based on the relation between active and reactive power change. The reactive power control mode can be configured by managing the reactive power directly and monitoring the voltage variation at the PCC. Therefore, the PV inverters shall be designed to have one or all of these control modes to achieve voltage regulation requirements.

The relevant TSO together with the local DSO should specify the boundaries of voltage, reactive power and active power using voltage and reactive power curves (*V*-*Q*) at the maximum rated capacity ($P_n$) or by using active and reactive power curves (*P*-*Q*) below the maximum rated capacity ($P_n$) [49]. These (*V*-*Q*) and (*P*-*Q*) curves are imposed in all of the reviewed grid codes in this thesis but with different specified boundaries for voltage, active and reactive power. The typical idea of these three control modes can be identified from ENTSO-E grid codes for (*V*-*Q*) and (*P*-*Q*) curves in figure 4.9 and figure 4.10. ENTSO-E grid code states that the PV power units of classes C and D shall have the ability to operate either in reactive power control mode, voltage control mode or power factor control mode [49].

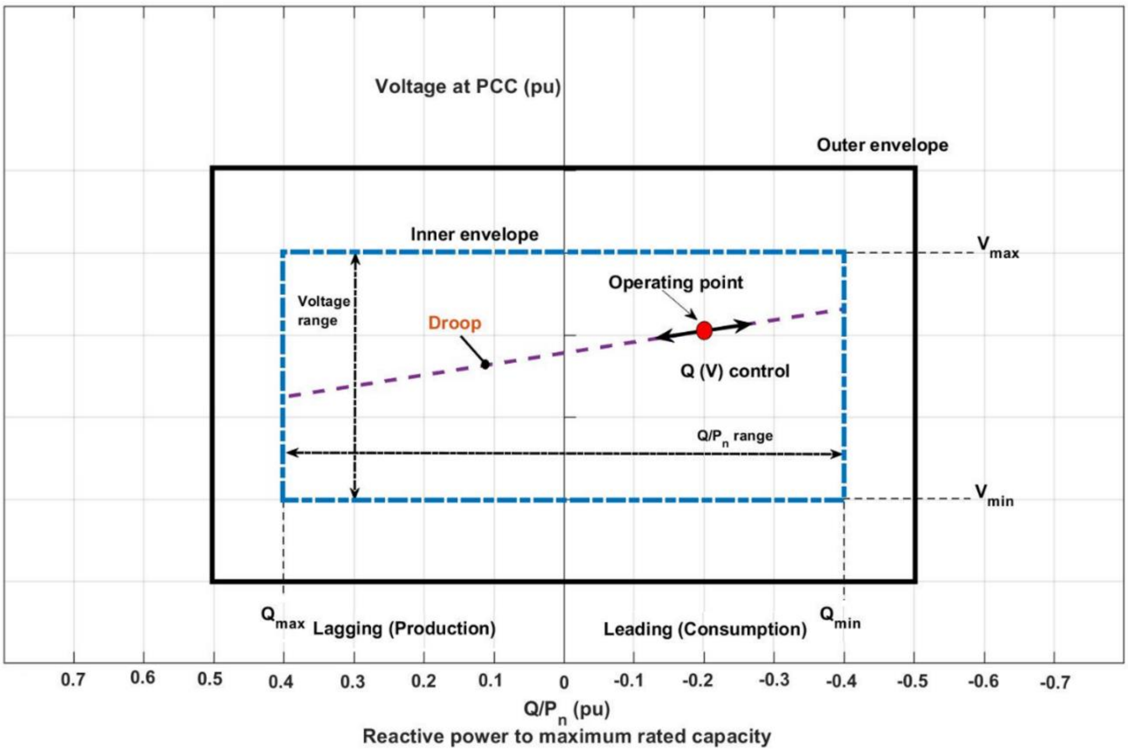


***Figure 4.9.*** *Reactive power control requirement typical idea to control the voltage at the PCC using Q(V) control mode by (V-Q) profile curve for PV power plant which operates at maximum rated capacity ($P_n$) imposed by ENTSO-E grid code* [49].

As seen in figure 4.9, the relevant TSO in each country shall stipulate the maximum and minimum boundaries for the inner envelope for voltage ($V_{min}$, $V_{max}$) and reactive power ($Q_{min}$, $Q_{max}$). By imposing a voltage reference operating point at the PCC, PV power plant must have the capability to contribute to the voltage stability by providing a reactive power support within its dynamic boundaries with the configured droop to restore the voltage again within its predefined values of the inner envelope. In this way, the voltage at the PCC can be controlled by controlling the reactive power of the PV power plant using $Q(V)$ control mode. When the voltage at the PCC has reached its dynamic specified limits, the control function shall be deactivated. The inner envelope range for the voltage and reactive power can take any shape according to the requirements imposed by each country's grid code but without exceeding the limits of the outer envelope.

For the PV power plants which operate lower than its maximum rated capacity $P_n$, they have to be capable of delivering reactive power at any operating point within the inner envelope boundaries which are specified by the relevant TSO as seen in figure 4.10. In this case, the voltage can be controlled at the PCC using reactive power control mode or power factor control mode.

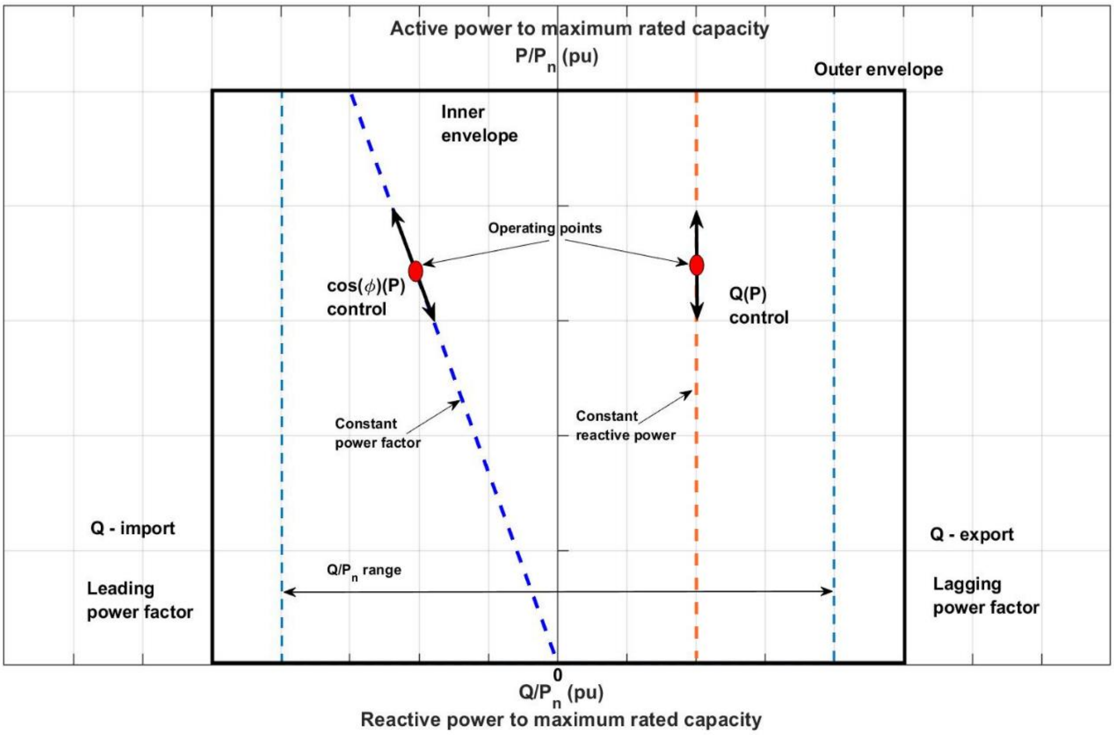


***Figure 4.10.*** *Reactive power control requirement typical idea to control the voltage at the PCC by Q(P) and cos ϕ(P) control modes by (P-Q) profile curve for PV power plant which operates below its maximum rated capacity ($P_n$) imposed by ENTSO-E grid code* [49].

The reactive power control mode can control the reactive power independently by regulating the active power at the PCC by activating *Q*(*P*) control mode of the PV power plant. The power factor control mode can control the reactive power directly by regulating the active power at the PCC by activating *cos ϕ*(*P*) control mode from the PV power plant. In case of *Q*(*P*) control mode, the relevant TSO shall specify the constant reactive power *Q* operating set point at which the PV power plant can increase or decrease its active power by the configured droop and hence, mitigating the voltage at the PCC. The same manner is implemented in case of *cos ϕ*(*P*) control mode, by setting a constant power factor operating set point and the PV power plant can mitigate its active power provision with the configured droop to control the voltage at the PCC. When the voltage at the PCC equals to the voltage set point range, the PV power plant has to stop providing the reactive power. PV power plants must be committed to achieve one or more of these three reactive power control modes functions according to setpoints and boundaries specified by the relevant grid code without reliance on tap changing transformer or other voltage regulation methods. PV power plants must be supplemented with the needed equipment or devices to achieve these setpoints remotely. Thus, the PV power plant's inverter has to be designed to have at least one of these control modes to contribute to the voltage control at the PCC as requested by the relevant TSO for each country.

A chart comparison for the requirements and boundaries which are imposed by the international grid codes for these three control modes is implemented in figures 4.11 and 4.12. It can be seen from figure 4.11 that each grid code has imposed the dynamic requirements of the reactive power by which the PV power plant shall activate its Q(V) control mode to mitigate any change in the voltage at the PCC. The required droop at which *Q*(*V*) mode shall operate can be configured by the relevant TSO in each country. For instance, Danish grid code is demanded from PV power plants of category C to provide a dynamic reactive power support between ±0.484 pu to stabilize the voltage within ±10% of the nominal voltage at the PCC. While, in case of category D PV power plants, the TSO shall enforce the dynamic range of reactive power during the operation. Finland, Egypt and Saudi Arabia has demanded ±0.33 pu of reactive power dynamic support to restore the voltage but with different operating ranges. The same reactive power dynamic requirements are imposed by the German grid code, but to stabilize the voltage within 0.87 pu to 1.15 pu at the connection point. Malaysia and Australia have enforced variable ranges for the reactive power support during leading or lagging operation. Malaysia has imposed a range between -0.33 pu and +0.623 pu while Australia has enforced a dynamic range between -0.484 pu and +0.33 pu.

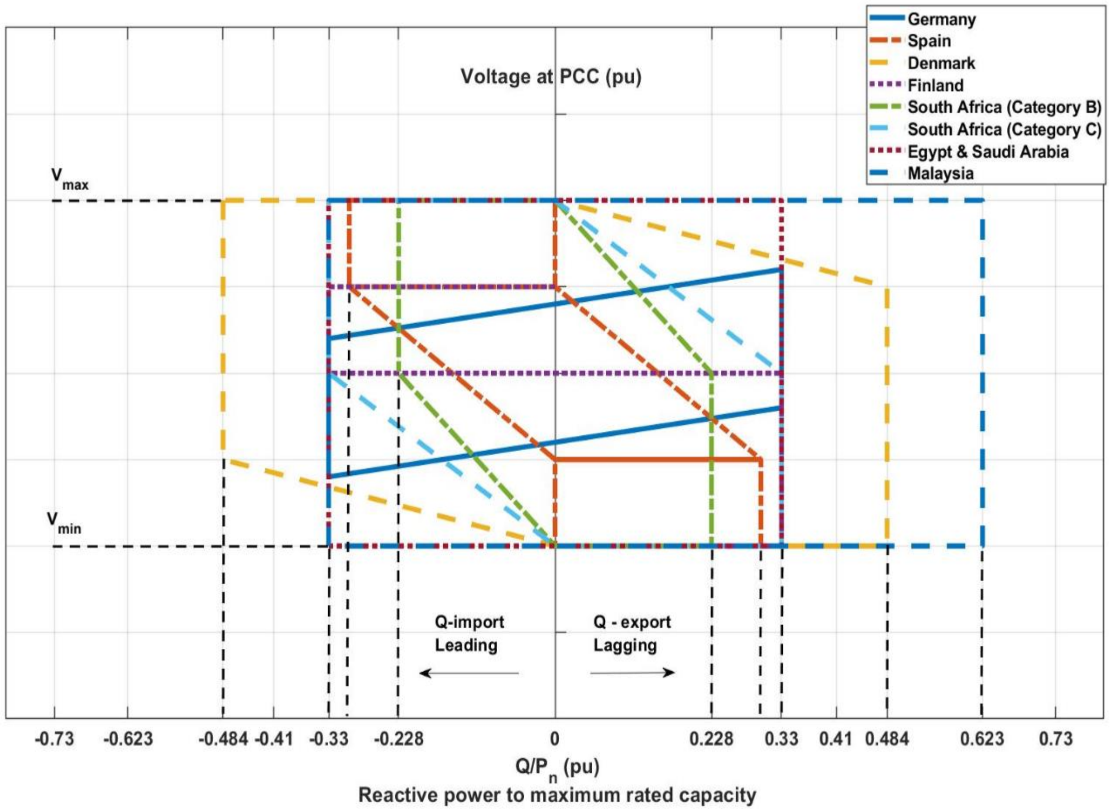


***Figure 4.11.*** *Reactive power control requirement comparison by using Q(V) mode for PV power plants to control the voltage at the PCC imposed by international grid codes.*

In figure 4.12, the reactive power can be controlled by activating *Q*(*P*) or *cos ϕ*(*P*) control modes within the specified requirements imposed by the grid code in each country. The relevant TSO specifies the operating constant set point for reactive power or power factor and the PV power plant has to export an active power at the PCC to regulate the voltage, but not less than the specified limit at $P_{min}$. For instance, Finland and Egypt have stipulated that PV power plant can mitigate its active power at a power factor range of ±0.95 or with reactive power range of ±0.33 pu. The same way is imposed by other grid codes in all of the countries but within different requirements and ranges which can be seen in detail in table 8.

As per table 8, most of the recent grid codes have demanded that PV power plants have to be capable of operating with one or more of these reactive power control modes to mitigate the voltage at the PCC. Some of the grid codes have requested the three control modes from the PV power plant such as Germany, Denmark, Finland, Egypt, Australia and South Africa.

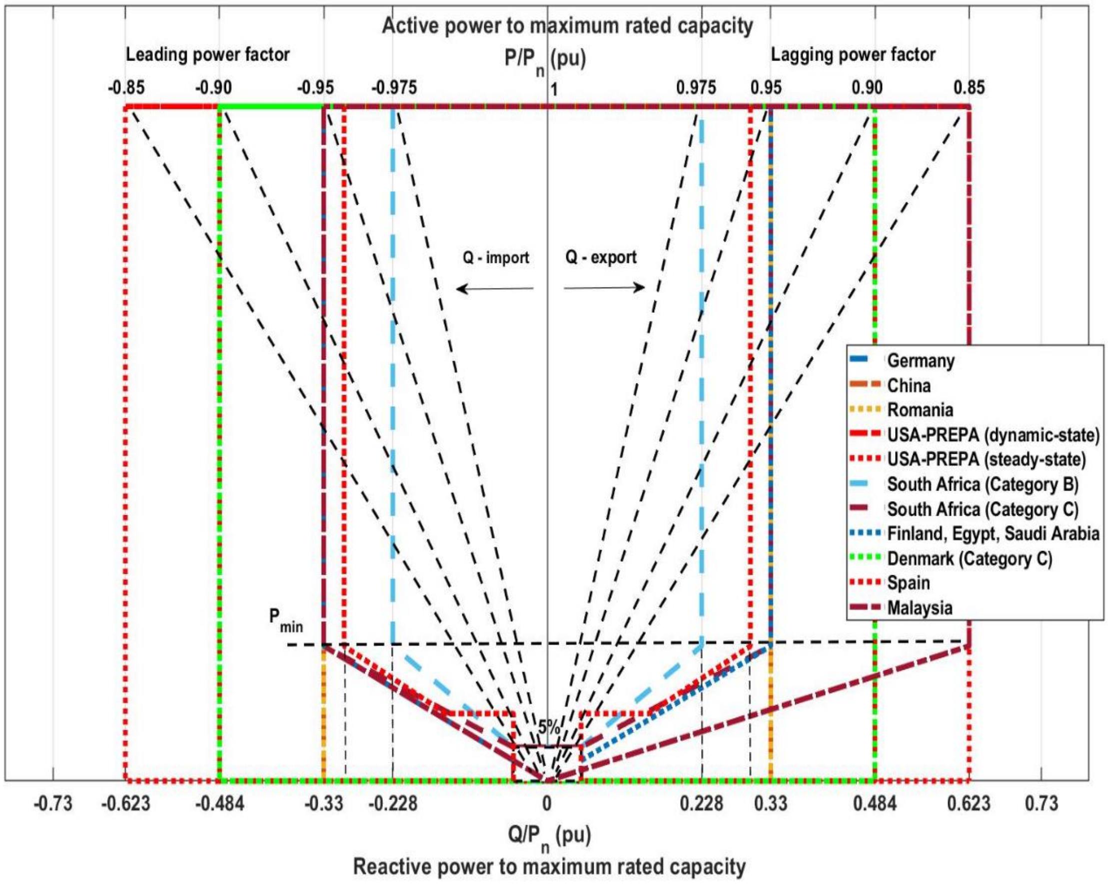


***Figure 4.12.*** *Reactive power control requirement comparison by using Q(P) and cos ϕ(P) control mode for PV power plants to control the voltage at the PCC, imposed by international grid codes.*

Other grid codes such as Spain, Italy, Saudi Arabia and Malaysia have demanded two modes which have to be supplemented with the PV power plant. USA-PREPA requests only one reactive power control mode during its steady state and dynamic operation. It can also be decerned that, as the PV power plant rating is increasing, the more requirements are being requested for power factor and reactive power ranges. For example, in South Africa, the reactive power range for PV power plants of category C is between ±0.30 pu with power factor range between ±0.975, while the reactive power range of category B is between ±0.228 pu with power factor range between ±0.90. Also, Danish grid operator is imposed a full range of reactive power support agreed with the TSO from the PV power plants of category D with a power factor range between ±1. China and USA-PREPA have imposed only one mode of reactive power control using *Q*(*P*) mode to control the voltage at the PCC.

***Table 8.*** *Comparison of reactive power control requirements to control the voltage at the PCC for PV power plants operate at different control modes set points imposed by international grid codes (AGO*: Agreed with grid operator, NS*: Not stipulated in the grid code).*

| **Grid code by country** | **Voltage range (pu)** | | **Reactive power range (pu)** | | **Power factor range *cos ϕ*** | | **Control mode function set points** | | |
|---|---|---|---|---|---|---|---|---|---|
| | $V_{min}$ | $V_{max}$ | $Q_{min}$ | $Q_{max}$ | Lead | Lag | *Q(V)* | *cos ϕ(P)* | *Q(P)* |
| **Germany** | 0.87 | 1.15 | -0.33 | +0.33 | 0.95 | 0.95 | √ | √ | √ |
| **Spain** | 0.95 | 1.05 | -0.30 | +0.30 | 0.90 | 0.90 | √ | NS* | √ |
| **Finland (C & D)** | 0.90 | 1.05 | -0.33 | +0.33 | 0.95 | 0.95 | √ | √ | √ |
| **Egypt** | 0.90 | 1.10 | -0.33 | +0.33 | 0.95 | 0.95 | √ | √ | √ |
| **Saudi Arabia** | 0.95 | 1.05 | -0.33 | -0.33 | 0.95 | 0.95 | √ | NS | √ |
| **Italy** | 0.90 | 1.10 | -0.35 | +0.35 | 0.90 | 0.90 | √ | NS | √ |
| **Denmark (C)** | 0.90 | 1.10 | -0.484 | -0.484 | 0.90 | 0.90 | √ | √ | √ |
| **Denmark (D)** | 0.90 | 1.10 | AGO* | AGO | 1.00 | 1.00 | NS | √ | √ |
| **Australia** | 0.85 | 1.15 | -0.484 | +0.33 | 0.90 | 0.95 | √ | √ | √ |
| **China** | 0.90 | 1.10 | -0.31 | +0.31 | 0.95 | 0.95 | NS | NS | √ |
| **Malaysia** | 0.90 | 1.10 | -0.33 | +0.623 | 0.95 | 0.85 | √ | NS | √ |
| **South Africa (B)** | 0.90 | 1.10 | -0.228 | +0.228 | 0.95 | 0.95 | √ | √ | √ |
| **South Africa (C)** | 0.90 | 1.10 | -0.33 | +0.33 | 0.975 | 0.975 | √ | √ | √ |
| **USA-PREPA (Dynamic)** | 0.85 | 1.15 | -0.623 | +0.623 | 0.85 | 0.85 | NS | NS | √ |

In this section, it can be perceived that the reactive power control function is essentially required from PV power plants to control the voltage at the PCC. It is hard to determine a specific common range for the reactive power range in all of the reviewed grid codes, but it is often variate in between ±0.484 pu while, the power factor often variates between ±0.90 in all of the grid codes. At least one of the control modes of *Q*(*V*), *Q*(*P*) or *cos ϕ* (*P*) has to be demanded from the PV power plants to contribute to the voltage regulation. It can be observed that *Q*(*P*) control mode is requested by all of the reviewed grid codes. Thus, it can be considered as the minimum requirement for the PV inverter to contribute to voltage control. The other two control modes can be considered as a future requirement that shall be considered by the PV owner in their future design of the PV inverter. In the near future, most of the grid codes will require all of the three control modes, which shall be supplemented with the PV inverter to give a broader range of dynamic performance for the voltage control.

## 4.5 Frequency and active power control

Frequency control during steady state operation is intended to maintain the frequency during normal operating conditions if network frequency fluctuates gently within the specified operating limits. It is well known that active power production has to be in balance with the load demand to preserve the network frequency ($f_n$) at its nominal value either 50 Hz or 60 Hz. During imbalance event between the power production and load demand, the network frequency starts to deviate, and conventional synchronous generators tends to restore the frequency to its nominal value by its governor control. This control has to be initiated directly to avoid the frequency from large deviation over or under its dead band limits. With the high penetration of PV power plants to replace these conventional generators, several studies show that more frequency variation and instability issues are presumed to occur [66,67] . Thus, modern grid codes require that PV power plants inverters have to be supplemented with the primary frequency control capability function to contribute to frequency stability at the PCC. The idea of primary frequency control function is, in case of frequency deviation, it is demanded from the PV power plant to change its active power output by a certain amount agreed with the relevant TSO to stabilize the frequency within its threshold dead band limits. Most of the grid codes enforce requirements for this active power regulation in response to overfrequency deviation which can be called limited frequency sensitive mode of overfrequency (LFSM-O). This mode means that the PV unit must have the ability to decrease its active power output linearly by a specified droop percentage in case of the frequency crosses over the imposed threshold limit. On the other hand, only few grid codes impose specifications during underfrequency variation which can be called limited frequency sensitive mode of underfrequency (LFSM-U). In this mode, it is demanded from the PV power plant to increase its active power output linearly by a specified droop percentage when the frequency is below an imposed threshold limit.

The typical curve for active power control requirements during under or overfrequency deviation can be presented from the German grid code as seen in in figure 4.13. It can be observed that the dead band of frequency in normal operation is between 49.8 Hz and 50.2 Hz. In case the frequency at the PCC exceeds the dead band boundaries, the PV power plant is demanded to provide an active power control by upward or downward regulation droops based on equation 2.

$$\Delta P = \begin{cases} 20 * P_{pre} * \dfrac{49.8\ Hz - f_n}{50\ Hz} & 47.5 \leq f_n \leq 49.8 \\ 20 * P_{pre} * \dfrac{50.2\ Hz - f_n}{50\ Hz} & 50.2\ \leq f_n \leq 51.5 \end{cases} \quad (2)$$

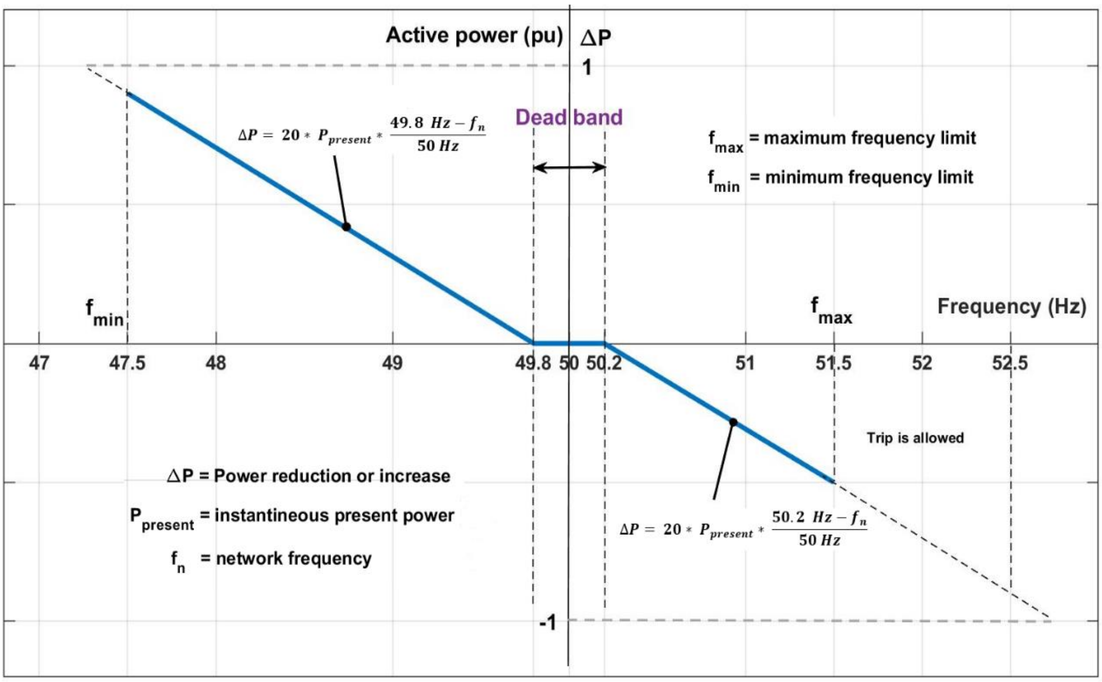


***Figure 4.13.*** *Frequency response requirement and active power control specifications for PV power plants during frequency disturbance imposed by German grid code* [51].

It can be seen from figure 4.13 that when the frequency has started to cross over 50.2 Hz, it is demanded from PV power to activate its LFSM-O function with configured regulation droop equals to 2% to restore the frequency within the dead band limit. In this situation, the PV power plant has to curtail its active power in steps linearly by *ΔP* value following equation 2. The same way is implemented during underfrequency disturbance, but it is requested from the PV power plant to increase its active power when the frequency starts to be less than 49.8 Hz. Both regulations shall be done within the minimum and maximum limits of frequency limits, otherwise trip is allowed.

A typical example for underfrequency response can be seen in figure 4.14 from Fingrid grid code. In case the frequency is below $f_u$, the PV power plant has to activate its LFSM-U function within 2 seconds when the frequency at the PCC has started to be below $f_u$ value of 49.5 Hz. Thus, the PV unit must increase its active power output linearly with adjustable droop between 2% and 12%. The PV power unit can implement this upward frequency regulation until a specified minimum frequency value agreed with the Fingrid TSO.

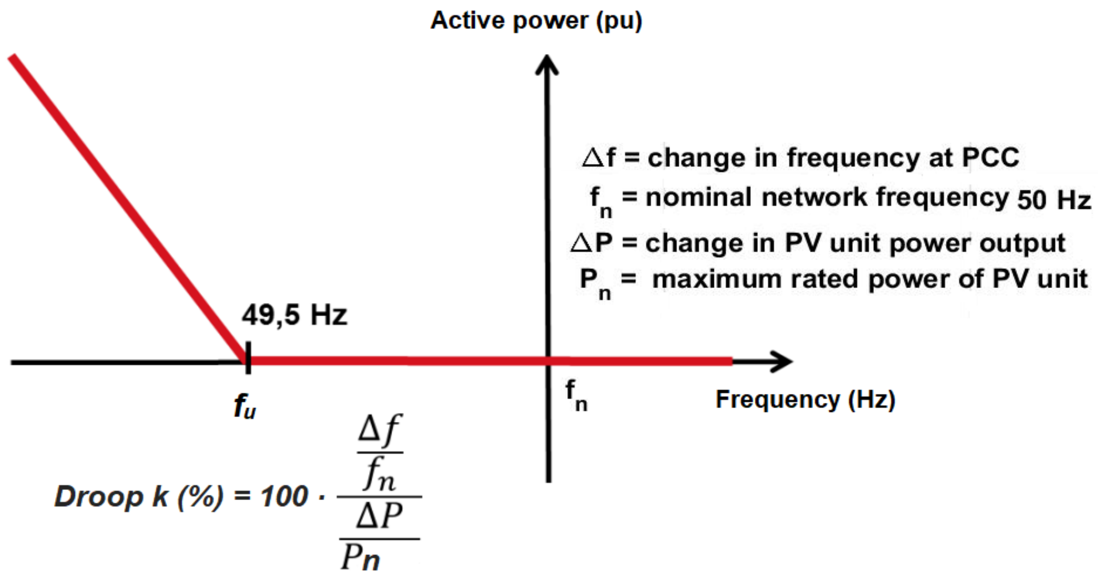


***Figure 4.14.*** *LFSM-U requirement response to control the PV power plant's active power during underfrequency disturbance imposed by Fingrid grid code* [48].

A chart comparison for the frequency response and active power control specifications between the international grid codes can be seen in figure 4.15. During overfrequency deviation above 50.5 Hz, it can be seen that Egypt and Malaysia have demanded from PV power units to activate their LFSM-U function and start to reduce their active power production to mitigate the frequency within it dead band at the PCC. This active power reduction can continue linearly by the configured droop but until a minimum value of $P_{min}$ at 0.40 pu from PV rated capacity. The same is imposed in Spain but until $P_{min}$ equals

0.50 pu when the frequency crossed over 50.2 Hz with 5% of downward regulation droop. The Italian grid code demands that the PV power plant has to activate its overfrequency control function when the frequency is between 50.3 Hz to maximum frequency 51.5 Hz by reducing its active power output with a downward regulation droop *k* is equal to 2.4%.

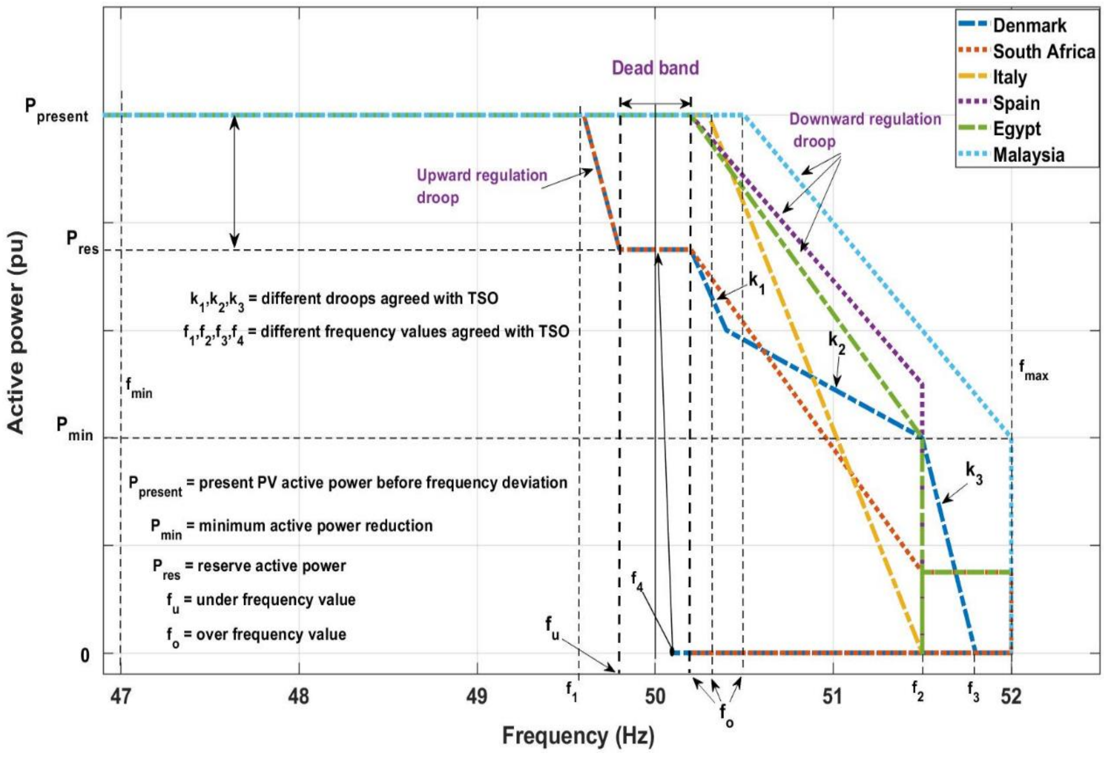


***Figure 4.15.*** *Active power control requirements' comparison for PV power plants to control the frequency at the PCC during frequency disturbance imposed by international grid codes.*

The grid codes in Denmark and South Africa demand a variable downward and upward droop regulation from the PV power plants to decrease or increase their active power output in case of frequency deviation. For example, Danish grid code is enforced three different downward droop regulation ($k_1$, $k_2$, $k_3$) when the frequency has started to be over $f_o$. These different droop regulations shall be agreed and enforced by the TSO in Denmark. In South Africa, upward droop regulation is enforced when the frequency is below $f_u$ and until $f_1$, the PV power plant shall be designed with the capability of providing a reserve active power ($P_{res}$) of not less than 3% of $P_{present}$. $P_{res}$ is the amount of active power by which the available active power has been reduced in order to provide reserves for frequency stabilization during LFSM-U capability. The values of $f_1$, $f_2$, $f_3$ and $f_4$ can be specified between the minimum and maximum frequency agreed by the relevant TSO.

A detailed comparison of these specifications and requirements for active power control and frequency response between all the reviewed international grid codes is presented in table 9.

***Table 9.*** *Frequency response requirements' comparison for PV power plants during under or overfrequency disturbance imposed by international grid codes (AGO*: Agreed with the grid operator, NS**: Not stipulated in the grid code).*

| Grid code | Frequency range | | Droop | Frequency response functions | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | (LFSM-O) | | | (LFSM-U) | | |
| | (Hz) $f_{min}$ | (Hz) $f_{max}$ | (%) $k$ | (Hz) $f_o$ | (Hz) $f_{max}$ | (pu) $P_{min}$ | (Hz) $f_u$ | (Hz) $f_{min}$ | (pu) $P_{res}$ |
| **Germany** | 47.5 | 51.5 | 5 | 50.2 | 50.8 | 0.75 | 49.5 | 47.5 | 0.8 |
| **Spain** | 47.5 | 51.5 | 5 | 50.2 | 51.5 | 0.50 | 49.5 | 48.5 | 0.9 |
| **Finland** | 47.5 | 51.5 | 2-12 | 50.5 | 51.5 | AGO* | 49.5 | NS** | AGO |
| **Italy** | 47.5 | 51.5 | 2.4 | 50.3 | 51.5 | 0 | NS | | |
| **Denmark** | 47 | 52 | 2-12 | AGO | | | AGO | | |
| **Egypt** | 47.5 | 51.5 | 4 | 50.2 | 51.5 | 0.40 | NS | | |
| **South Africa** | 47 | 52 | 0-10 | 50.5 | 51.5 | 0.25 | AGO | | 0.97 |
| **Saudi Arabia** | 57 | 62.5 | 4 | AGO | | | 59.5 | 57 | 0.90 |
| **USA-PREPA** | 56.5 | 62.5 | 5 | AGO | | | AGO | | |
| **Malaysia** | 47 | 52 | AGO | 50.5 | 52 | 0.40 | 49.5 | 47 | 0.95 |

In China, the grid code does not mandate any active power reduction function and just requires the PV facility to withstand the overfrequency event (50.2-50.5 Hz) within 2 minutes. Otherwise, the trip is mandatory. Fingrid regulation states that the power generating facility must be capable of reducing its active power production as a linear function of frequency when the electricity system's frequency exceeds 50.5 Hz with recommended droop at 4%. capacity. The relevant TSO in each country in this case can enforce a droop range *k* between 2% to 12%. However, the PV unit under LFSM-U mode shall consider the availability of the primary energy source like solar irradiance and the operating conditions especially the limitations on operation close to the maximum capacity at low frequency before activating its frequency response function.

### 4.5.1 Active power constraints functions

Some of the grid codes demand additional supplementary automatic functions for active power control which can be identified as absolute power constraint, delta power constraint and ramp rate constraint. The main purpose of these control functions is to constrain the PV unit active power within limits to maintain the network frequency stability during the changes of the intermittent resource. The absolute power constraint function which can be known as active power curtailment (APC) is used to restrain the active power of PV power plant to a predefined maximum value to protect the grid from excessive loading during overfrequency deviation. The delta power constraint function is used to implement power reserve in response to the upward frequency control to mitigate the PV power output to a desired value not more than its rated active power. This function can be defined as a spinning active power reserve (APR) capability during the underfrequency response as mentioned earlier in figure 4.15. The ramp rate constraint (RRC) function is used to mitigate the maximum speed by which the active power output can be increased or decreased corresponding to the variability of solar irradiance during frequency deviations. This ramp rate control capability can be used to prevent the adverse impacts on the stability of the grid utility due to variations in the active power of PV plants.

The main idea of operation for these supplementary active power control functions stipulated by the grid codes in Denmark and South Africa can be seen in figure 4.16. The green curve is the normal active power performance of the PV power plant, while the red curve is the PV active power output after activating the three function based on the constraints which are imposed by the relevant TSO. It can be seen that the APC function has to be activated to mitigate the PV power output at a constant value as long as its available power is more than this predefined absolute power constraint. In case of the PV output power is being increased or decreased with a rate higher than the predefined ramp rate constraint, the upward or downward RRC function has to be activated. For example, in Denmark, PV power plants are committed to have a protection function through which PV power output can be curtailed to a predefined value. PV plants must have at least five configurable set points up to 70%, 50%, 40%, 10% and 0% to which active power output can be decreased in steps [50]. ENTSO-E also requires that PV unit shall be equipped with logic interface option for terminating their power production within 5 seconds after receiving a cease signal from TSO to activate the power curtailment function [49].

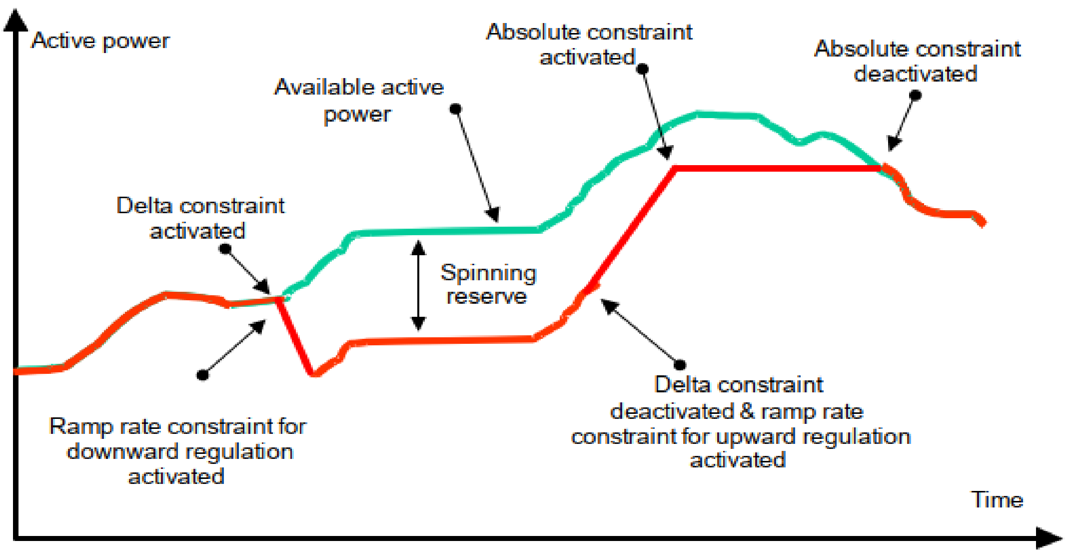


***Figure 4.16.*** *Active power constraints functions' general curve imposed by grid codes in Denmark and South Africa* [50,57].

Several grid codes have imposed certain requirements for the ramp rate control function during upward ramp or downward ramp of PV active power output. Denmark and South Africa demand a certain percentage of ramp rate control of PV power plants as agreed with their TSO. The Puerto Rico electric power authority has imposed a 10% per minute for upward or downward ramp rate on PV plant connected to its grid. Romania has also enforced 10% of upward ramp rate constraint while Germany has imposed 1% of upward ramp rate control per minute are demanded from PV power plants. Different RRC function requirements imposed by different international grid codes can be seen in table 10.

***Table 10.*** *RRC requirement comparison for active power control of PV power plant imposed by international grid codes (NS*: Not stipulated at the grid code).*

| Grid code by country | Active power ramp rate percentage per minute |
|---|---|
| **Germany** | 1% |
| **USA-PREPA** | 10% |
| **Finland** | 10% |
| **Romania** | 10% |
| **South Africa** | According to TSO |
| **Denmark** | According to TSO |
| **China** | NS* |
| **Spain** | NS |
| **Malaysia** | NS |
| **Italy** | NS |
| **Egypt** | NS |
| **Australia** | NS |
| **Saudi Arabia** | NS |

It can be observed from this section that PV power plants have to contribute to the frequency regulation at the PCC by controlling their active power with several functions which are imposed by the relevant TSO in each country. These functions can be activated during over or underfrequency deviation with specified requirements imposed by each grid code. Most of the modern reviewed grid codes require LFSM-O control function in response to the overfrequency deviation with APC capability to curtail the PV power plant active power in steps to restore the frequency within its dead band limits. Some of the reviewed grid codes require the LFSM-U function during underfrequency deviation with APR capability to implement an active power reserve from the PV power plant to regulate the frequency within its dead band limit. Few of the grid codes demand to activate RRC function to constrain the PV unit active power ramps especially due to their intermittent solar irradiance. Thus, LFSM-O function with APC capability can be considered as a minimum requirement which has to be supplemented with PV inverters in all of the grid codes. While, LFSM-U function with APR capability can be counted as a future requirement which shall be considered in the future design of PV inverters. RRC function still not stipulated in most of the grid codes, therefore it is still under discussion and research.

Most of grid codes have referred that the frequency and active power control must be agreed with the relevant TSO before activation. It can be observed also that the supplementary active power functions such as APC, RRC and APR are recently added in few grid codes to be demanded from PV power plants. However, these functions will become essential in all of the grid codes in the near future as long the high penetration of PV power plants into the power system. This is because of their positive impact to enable the PV power plants to perform as the conventional generators in case of normal operation or disturbances. For example, the active power curtailment function can have a significant impact not only for transmission network but also for distribution network. It can support the DSOs to avert network reinforcements costs by installing new transformers or conductors with higher capacities in case of overloading. This is rather common when dealing with power generating modules based on renewable energy since the highest need for active power curtailment arises during extreme scenarios when the local demand is at its minimum while at the local power generating modules operate at their maximum capacity.

## 4.6 Advanced requirements and functions

Due to the high contribution of large scale PV generation units to an exceptional level in many countries globally, grid codes are expected to further development for additional functions and requirements which may be demanded from PV power plants in the near future. These additional requirements and specifications shall give more dynamic performance of PV inverters to perform as the conventional synchronous generators during sudden disturbances. The sections below provide a brief overview of some of these technical requirements which are still under study and discussion in most of the reviewed grid codes. Only the new requirements are illustrated which include virtual inertia, black start capability and power oscillation damping.

### 4.6.1 Virtual inertia capability

Conventional power system can mitigate the sudden frequency disruptions by the stored energy in the revolving parts of the synchronous generators. In case of unexpected disturbance or sudden change between power production and load demand, the slow dynamics of the synchronous generators have to prevent these transients to achieve the power balance within the grid time regulations. The high contribution of PV power plants into the grid utility arises power system instability concerns due to the lack of rotating masses regardless their power ratings. This can lead to reduce the inertia in the power system and undermine its ability to overcome the sudden frequency fluctuations like disconnection of large generation power plant. In order to emulate the inertial response of the synchronous generator, PV inverter must be supplemented with virtual inertia function. The virtual inertia capability (VIC) is a combination of advanced control algorithms that enable the PV inverter to imitate the inertial behavior of a conventional synchronous generators as synthetic inertia [68]. Recently, more studies are developed to implement a practical approach for VIC based on different topologies of the used inverter which can be seen in [69] . Consequently, VIC is less demanded in most of the recent grid codes but, it will be required in the near future as the rapid growth of PV generation in many countries. Only few grid codes from the reviewed countries are stipulated the VIC requirement. For instance, ENTSO-E states that the relevant TSO shall have the right to stipulate that PV power units from C and D categories have synthetic inertia function to fulfil the control schemes specified by the local TSO [49]. However, this requirement is still not enforced yet for PV inverters at any of the reviewed grid codes as the conventional synchronous generators are still enough to implement the needed virtual inertia in the European system. Saudi Arabia grid code stipulates that PV power plants which are over 25 MW have to activate their VIC to contribute in providing synthetic inertia in case of frequency sudden disturbance. Spanish grid code demands from PV power plants of class C and D to provide inertia emulation with VIC matching specified continuous control system agreed by the TSO to increase or decrease their active power in proportional to the time derivative of frequency disturbance at the point of connection to the grid. In the event that this function is requested, the system operator will provide the PV power plant owner with detailed specifications regarding the control schemes to be implemented and parameters and the relative requirements shall subsequently be formalized in the grid code regulations. Such implementation still requires considerable design effort and research work which may also entail supplementary devices and equipment such as storage systems for effective operation of inertia emulation. Once these researches and effective results have been accomplished, such VIC requirements can support to raise the level of PV power plants penetration into the power system. Thus, implementation of VIC requirement would facilitate and escalate the expansion in large scale deployment of PV generation plants into the power grid.

### 4.6.2 Black start capability

System grid operators must have the ability to restart their large transmission and power system without external support by using their large synchronous generators in the network. These large generation facilities are the main core from which the restoration process of the system can commence gradually stage by stage according to the grid regulations. The ability to start a generation plant without any electricity support from an external power source is defined as black start capability (BSC). Traditionally, synchronous generators in the present power systems are mainly responsible to implement BSC, and the various approaches using these generators are well understood. With the high levels of PV penetration as converter-based power plants, PV power plants alone cannot implement BSC, even if their primary power source is surplus available at a time when this function may be demanded. Some of the recent studies and projects have been implemented to use different configurations for BSC such as battery energy storage system to provide black start capability support for PV power plants [70]. In the situation of black start restoration, PV power plant will perform in island mode without any external support from the main grid. So, the main challenge of this function is to provide effective voltage control and frequency control during this islanding operation to achieve a quick balance between the generation and the load demand. Thus, to implement this BSC requirement with PV power plants, it must be supplemented with energy storage or small conventional generation unit to ensure fast response and efficient frequency and voltage control. Consequently, PV power plants owners have to consider these additional equipment and devices in their design to ensure the activation of BSC function according to each grid code regulations. Only few codes demand BSC from PV power plants, but it must be agreed between the system grid operator and the PV owner. For instance, ENTSO-E states that BSC is not mandatory without prejudice to the relevant TSO to introduce obligatory rules in order to ensure system security. The local TSO in each country may make such a request if it considers system security to be at risk due to a lack of BSC in its control area. All the reviewed grid codes in Europe still not stipulated this function from PV power plants in their connection code as they still have enough conventional synchronous power plants to be able to implement system restoration.

### 4.6.3 Power oscillation damping

The oscillations which result from conventional synchronous generators can lead to damage the generator shafts if it is not damped efficiently. In case an external disturbance happens in any power system, power oscillations can be established and may cause a serious outage of large generation units. To avoid this situation, grid system operators require to damp these adverse oscillations to maintain the power system stability. Therefore, the control systems of large generation facilities have to fulfill the power oscillations and damping it to avoid the power system instability. Most of synchronous conventional power plants have this ability in their control systems by activation POD function. With the level of PV power plants contribution to the power systems, power oscillations damping issues are highlighted. Recently, several studies have started to investigate how PV power plants can perform during power oscillations disturbances as PV power plants may be required in a way to contribute to power oscillation damping. In the future, PV inverters have to activate POD capability according to the regulations mentioned in each country grid code. For example, ENTSO-E states that PV power plant shall be capable of contributing to damping power oscillations if it is demanded from the relevant TSO. Fingrid has also mentioned that PV power plants of class C and D shall be supplemented with POD function or power system stabilizer if it is requested by the system operator from the PV owner. The grid code in Saudi Arabia has requested that PV power plants which are all over 25 MW shall be supplemented with POD function by increasing or decreasing their power output in a certain way to mitigate the power oscillations in the low frequency range. Only few countries in Europe have stipulated POD requirement clearly in their grid codes for PV power plants such as Spain, Finland and Italy. But at the same time, they are following the same regulations which are mentioned according to ENTSO-E grid code regulations. Thus, it can be observed that POD function is still under development in most of the reviewed grid codes and it will be essential as the penetration of PV generation is increasing rapidly in the future. Table 11 shows, in which grid codes these advanced requirements have been stipulated clearly in their connection code for PV power plants. Only Finland, Spain, Italy, Saudi Arabia and Australia have been stipulated POD function clearly in their grid codes. BSC function is not stipulated at any of the reviewed grid codes. While, the other countries are still not stipulated these functions clearly in their regulations, but it is expected that these requirements will be imposed in most of the grid codes in the near future.

*Table 11. Comparison for advanced functions' requirements for PV power plants imposed by international grid codes (NS*: not stipulated in the grid code).*

| Grid code | Advanced functions requirements | | |
|---|---|---|---|
| | VIC | BSC | POD |
| **ENTSO-E** | √ must be agreed with local TSO in each country | √ must be agreed with local TSO in each country | √ must be agreed with local TSO in each country |
| **Germany** | NS* | NS | NS |
| **Finland** | NS | NS | √ |
| **South Africa** | NS | NS | NS |
| **Denmark** | NS | NS | NS |
| **Spain** | √ | NS | √ |
| **Malaysia** | NS | NS | NS |
| **Italy** | NS | NS | √ |
| **China** | NS | NS | NS |
| **Saudi Arabia** | √ | NS | √ |
| **Egypt** | NS | NS | NS |
| **Australia** | NS | NS | √ |
| **USA-PREPA** | NS | NS | NS |
| **Romania** | NS | NS | NS |

# 5. KEY CONSIDERATIONS AND CONSECUTIVE SUMMARY

This section sets a consecutive summary of the grid codes requirements and their technical specifications. It also highlights the essential key considerations for the PV power plants which have to be considered in the PV inverter design.

The voltage and frequency permissible boundaries of continuous operation have to be ensued by the PV power plants to avoid breakdown for the equipment and to maintain network stability. It can be noticed that the permissible voltage tolerance in most of the grid codes is often ±10% from the nominal voltage at the PCC. While, the permissible tolerance for the frequency often variates between ±3% of the nominal network frequency. In case the voltage or frequency have exceeded these boundaries, the PV inverters have to be designed to continue performing in a limited time or trip instantly, based on the magnitude of the disturbance which is specified by each grid code. Thus, the protection functions of voltage and frequency deviations in steady estate operation are essential and have to be considered for the PV inverters design.

In case of faults such as voltage dip or swell, the PV power plants as a generation facility has to ride through the faults and remain connected to the grid to maintain the power balance in the system. It is also demanded to provide a reactive current support to restore the voltage again between the permissible voltage dead band after the fault is cleared. During voltage dips, LVRT and RCS injection functions are essential in all of the grid codes while, the HVRT with RCS absorption are still not stipulated in some of the grid codes. The reactive current support is dependent on a droop function which variates between 2% to 12% in most of the grid codes and its maximum magnitude should not exceed the nominal rated current of the PV power plant. Thus, for large scale PV power plants, PV inverters must be designed at least with LVRT and RCS injection functions to ride through the voltage dip in order to avert power imbalance at the PCC. For more efficient operation as conventional power plants, HVRT with RCS absorption functions have to be considered from the PV power plants in case of voltage swell but, it will impact the total cost of the PV power plant.

Regarding the reactive power control and voltage regulation, the PV power plants must contribute to voltage control at the PCC by different modes of reactive power control. These control modes can regulate the voltage directly by constant voltage control set point or constant reactive power set point, or independently by controlling the active power at the PCC by setting a constant power factor set point. The reactive power control range in most of the grid codes is often between ±0.33 pu with a power factor range between ±0.90 to regulate the voltage between ±10% at the PCC. As the PV power plant is supported with more reactive power set points' capabilities within a wide range of control, it allows higher penetration of PV power plants into the network. This is because it can emulate the same performance of conventional power plants in voltage control and it can also reduce the probability of network reinforcements due to this high integration level such as adding STATCOM or SVC for additional voltage control range capabilities. Thus, the PV inverters have to consider the reactive power control capabilities as essential requirements into their design to implement a flexible dynamic voltage control contribution. As more capabilities of reactive power set points are supplemented with the PV inverter design, a significant impact on the PV power plant cost can be noted.

Regarding the frequency response and active power control, the PV power plants have to contribute to the frequency control during small frequency deviations or during sudden frequency disturbance to maintain the power balance at the PCC. This contribution can be achieved by controlling the active power provision or reduction of the PV power output. Most of the grid codes require LFSM-O capability in case of overfrequency disturbance by reducing the PV active power injected to the network to avoid excessive generation. While few of the grid codes require LFSM-U capability in case of underfrequency by increasing the PV active power injected to the network so as to avoid load shedding. Additional active power capabilities can be considered in order to implement a flexible dynamic operation as conventional power plants corresponding to frequency disturbances. These capabilities include APC, APR and RRC and they are mainly used to constrain the active power with a predefined set points to maintain the power balance during solar irradiance variability. The APC function is required in most of the grid codes with LFSM-O requirement from the PV power plants to start curtailing its active power output gradually to restore the frequency to its specified dead band value. APR function can implement a power reserve with LFSM-U requirement to restore the frequency to its specified dead band value in case of underfrequency. The RRC requirement is an essential function to constrain the PV power output ramps that occurs due to the intermittent solar irradiance. The positive ramp increase can be restricted by limiting the power injection ramp rate. The negative ramp decrease can be mitigated by harnessing an active power reserves which can be only used in case of dramatic decrease of PV power output. Both APR and RRC capabilities still require more discussion and research due to the issues related to the intermittency nature of the PV power plants and the power market especially the necessity of providing additional reserves in case of high level of contribution of large scale PV power plants. Thus, PV inverters have to be designed at least with APC and LFSM-O requirement in case of frequency response and active power control. However, supplementing more active power functions by PV inverters will contribute efficiently in system stability but at the same time, it will impact the PV power plant total cost significantly.

Regarding the future advanced requirements which can boost the present requirements and enhance the ability of PV power plants to perform as the same dynamic performance of conventional synchronous power plants during steady state and dynamic operation. These advanced requirements include virtual inertia (VIC) contribution, black start capability (BSC) and power oscillation damping (POD).

With the high penetration level of PV power plants which have zero rotating masses, the VIC will be an essential requirement in all of the grid codes in the near future. This is because the synchronous generators will no longer have the ability to provide enough inertia in case of higher percentage of converter-based PV power plants into the grid. Therefore, the PV inverters have to consider the VIC function as an essential capability in their design to emulate a hidden inertia with advanced control schemes in case of large disturbances in the network. Most of the TSOs still have enough synchronous generators to provide the required inertia into the network. Thus, this special control design of virtual inertia capability may take some time until it can be enforced in the grid codes.

The BSC requirement of PV power plant is hardly to be implemented alone even if there is a surplus availability of solar irradiance when this function is requested from TSO. This is because, the PV power plant in this case will act as an island and has to deliver an efficient voltage and frequency control during the restoration procedure to implement a quick balance between the generation and the load demand. Consequently, this BSC function will always require an additional energy storage or a conventional generator to be implemented successfully for quick power balance. Thus, this requirement is still under discussion and requires more research so as to be stipulated in the grid codes. Therefore, PV power plants' owners may consider additional requirements of energy storage or small conventional generators that have to be supplemented with their plants to support this requirement in the future, resulting in additional cost.

Regarding the POD capability, large deployment of PV power plants may be obliged to contribute in damping the power oscillations which caused by the present large conventional power plants to avoid equipment damage. This contribution requires more research and study especially with the high penetration of PV power plants as it might change this oscillatory behavior of large transmission systems. It might be required from the PV power plants to contribute to such oscillation damping only within small synchronous area. Therefore, this POD capability is still under discussion and research to be enforced in the grid codes in the future.

It can be summarized that the minimum modern technical requirements that are demanded from PV inverters in all of the reviewed international grid codes are LVRT requirement with RCS injection, voltage control by at least one mode of reactive power control mostly is $Q(P)$ setpoint, and LFSM-O requirement with the APC function for frequency stability in case of overfrequency disturbance. The future technical requirements include HVRT requirement with RCS absorption function during overvoltage disturbance, voltage control with more modes of reactive power control either Q(V) set point or cos (P) set point, LFSM-U requirement with APR and RRC functions for frequency stability, synthetic or virtual inertia (VIC), BSC and POD requirements. These functions vary from grid code to another based on their specific requirements in each country grid code.

# 6. CONCLUSIONS AND FUTURE WORK

The purpose of this thesis is to define the minimum and future technical requirements which are enforced in the modern global grid codes and which are demanded from PV power plants to be integrated into distribution and transmission networks. As the level of integration of PV power plants into the power system is rapidly escalating globally, issues of power system stability, reliability, security and power quality have been aroused significantly due to their intermittency nature. Therefore, various TSOs around the world have been driven to update their connection grid codes by imposing specific technical requirements and regulations which have to be ensued by PV power plants' owners to be allowed to interconnect into their power networks. These technical requirements and functions have to be considered in the early design of PV inverters according to each country grid code.

Firstly, the impact of large scale penetration of PV power plants as an intermittent distributed generation facility is investigated on the power system. In the distribution network, this impact can disrupt the voltage stability, network protection, reliability and power quality by causing voltage rise, voltage unbalance, voltage flickers, unintended islanding and voltage disturbances. In the transmission network, this impact can disturb the dynamic stability, voltage and frequency stability, system inertia provision, reactive power support and reliability during transmission faults due to its lack of rotating masses and the converter-based nature of PV power plants.

Due to this significant influence of vast contribution of PV power plants, a detailed study and comparison have been implemented to address the modern grid codes requirements which are imposed by the relevant TSO in different countries around the world. The thesis has only investigated the technical requirements regarding the connection code. These technical requirements include voltage and frequency permissible boundaries, fault ride through, reactive current support during voltage disturbance, reactive power control to regulate the voltage at the PCC and active power control to maintain the frequency at the PCC. These technical aspects have been analyzed within determined specifications, boundaries, constraints and time periods according to each country grid code. The more functions and capabilities accompanied with the PV inverters, the more flexible and dynamic operation can be achieved in order to implement the same performance of conventional synchronous power plants and hence, facilitating their integration into the power system.

It is found from the comparison and analysis that the minimum modern technical requirements and functions which have to be accompanied by the PV inverters in most of the grid codes are LVRT, RCS injection, voltage control, reactive power control, LFSM-O and APC capability. The LVRT requirement has to be accompanied by RCS injection function to ride through the fault and keep the PV unit connected to the grid during a limited period of time in case of voltage dip. The voltage control requirement has to be achieved by PV power plant through at least one mode of reactive power control, mostly $Q(P)$ control mode. By supplementing the PV inverter with more reactive power control functions of Q(V) and cos $\phi$(P) modes, the PV power plants can implement dynamic contribution in voltage control efficiently. The LFSM-O requirement has to be supplemented with APC function to reduce the active power of PV unit gradually with configured droop to contribute to the frequency control during overfrequency deviation but at the same time, it has to consider the RRC function to constrain the active power ramps.

The future and advanced grid codes requirements which are still under development or which require additional research projects are found as HVRT, RCS absorption, voltage control with power factor mode or reactive power mode, LFSM-U, APR, RRC, VIC, BSC and POD capabilities. In case of voltage swell, HVRT requirement has to be supported with RCS absorption capability to enable PV unit to remain operating and restore the voltage within its nominal value at the PCC. To achieve a wide range of voltage control ability, the voltage control can be established with either $Q(V)$ or cos $\phi$(P) modes to control the reactive power independently by controlling the PV power plant active power injection at the PCC. In case of underfrequency, additional power reserves with specific constrains of active power ramps can restore the frequency within its nominal dead band value by APR and RRC functions. VIC, BSC and POD requirements are still under investigation in most of the grid codes as there is enough conventional power plants in the present power system to provide enough inertia, black start restoration and damping the power oscillations.

The future work demands efficient studies and research to coherently investigate the influence of vast penetration of PV power plants into the power system, especially the issues related to the voltage and the frequency stability during sudden disruptions. These studies have to consider the present experiences and learnt lessons from other countries which have high level of share of PV power plants into their networks to identify the best practices so as to address an effective future grid code. There must be a coordination between the regional grid operators trying to unify their technical specifications, boundaries and limits to facilitate the process of establishing at least regional common grid code. Harmonization between the countries by sharing resources, knowledge and experiences will be the main core to implement a global standard grid code that can harmonize the requirements with common specifications for PV power plants integration and hence, support the PV owners to achieve the balance between the cost and the global standards and regulations.

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