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Review

Grid-connected renewable energy sources: Review of the recent integration requirements and control methods

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ABSTRACT

The growing of renewable power generation and integration into the utility grid has started to touch on the security and stability of the power system operation. Hence, the grid integration requirements have become the major concern as renewable energy sources (RESs) such as wind and solar photovoltaic (PV) started to replace the conventional power plant slowly. In line with this, some of the new requirements and technical regulations have been established to ensure grid stability. This study aims to fill the gap and conduct an updating review of the recent integration requirements and compliance control methods regarding the penetration of renewable power plants to the power grid. The review is conducted by a comparing of the key requirements related to voltage stability, frequency stability, voltage ride-through (VRT), power quality, active and reactive power regulations towards grid stability. In order to fulfill these requirements, different control methods have been recently proposed. Accordingly, this paper compares and reviews the state-of-the-art solutions for compliance technology and control methods. Furthermore, a broad discussion on the global harmonization of the integration requirements, challenges, advantages and disadvantages is also highlighted. The rigorous review indicates that although the recent integration requirements can improve the grid operation, stability, security, and reliability, further improvements are still required with respect to protective regulations, global harmonization, and control optimization. Various recommendations for future research related to the integration and technical regulations of RESs are then presented. In sum, the insights provided by this review may aid the development of smooth and stable grid integration of RESs, help developers and researchers to develop the design and control strategies in the sense of current requirements. Additionally, assist power system operators in establishing or improving their own requirements in comparison with the remaining international requirements.

Contents

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Nomenclature

BCC	Brake chopper circuit
DSO	Distribution system operator
DVR	Dynamic voltage restorer
ESS	Energy storage systems
EREC	European renewable energy council
EWEA	European wind energy association
GC	Grid code
GW	Gigawatts
HVRT	High-voltage ride though
IEC	International electro-technical commission
LVRT	Low voltage ride though
NERC	North American electric reliability corporation
ND	Not defined
PV	Photovoltaic
PCC	Point of common coupling
PREPA	Puerto Rico electric power authority
RES	Renewable energy sources
RPP	Renewable power plants
SDBR	Series dynamic breaking resistor
STATCOM	Static synchronous compensator
SVC	Static var compensator
THD	Total harmonic distortion
TSO	Transmission system operator
VRT	Voltage ride through
VUF	Voltage unbalance factor
ZVRT	Zero voltage ride through

1. Introduction

The usage of renewable energy sources (RESs) for generating electricity has attracted considerable attention around the world. This is due to the negative environmental impact of burning fossil fuel for energy conversion, which releases a tremendous amount of carbon dioxide and other greenhouse gasses to the atmosphere (Viteri et al., 2019; Dhinesh et al., 2018). Overall, conventional fossil fuels are a non-renewable type that poses a potential threat in the form of resource depletion. On a global scale, the annual consumption of 11 billion tons of fossil fuel and energy consumed from fossil fuels is 82.67% (Nanthagopal et al., 2019), which contributes to global warming and grid decarbonization (Aghajanzadeh and Therkelsen, 2019). To reduce emission and fuel consumption, bio-fuel energy is stated to be developed (Dhinesh and Annamalai, 2018). Besides, numerous RESs have been implemented in many countries such as wave, wind, hydro, solar and bioenergy (Uddin et al., 2018). As one of the diversified renewable energy solution, the biomass was used to produce renewable electricity, thermal energy, or transportation fuels (biofuels). It was used for bio-energy production by pyrolysis (Biswas et al., 2017a), hydrothermal liquefaction (Biswas et al., 2017b), and gasification (Biswas et al., 2016). Regarding electrical power generation, the most advanced RESs that have been widely integrated with the main power grid in several areas worldwide are solar photovoltaic (PV) and wind (Giallanza et al., 2018). However, due to their intermittent availability, wind and solar energy sometimes required energy storage devices (Barton and Infield, 2004). The integration of RESs that are dependent on the weather conditions can impact the stability, quality, and reliability of the utility grid. Therefore, various standards, requirements, and regulations concerning the operation and connection of these RESs have been imposed and updated by the grid codes (GCs) and other standards of various countries (Al-Shetwi and Sujod, 2018c). GC contains a variety of technical specifications that describe important rules and restrictions associated with the generation units and their integration into the power grid to ensure the stable and appropriate operation of the power system (Islam et al., 2019a).

Even though some renewable energy generators have been linked with the transmission system, the majority of such generators have been connected with the distribution system. The transmission system operators (TSOs) and distribution system operators (DSOs) have faced a significant increase in the level of penetration of RESs, particularly solar PV and wind, as well as from a plethora of other strategies introduced to replace traditional power plants with RESs (Li et al., 2019). These changes have forced the operators of electrical systems to consider the effect of this penetration on the stability of the grid. New regulations have been introduced by TSOs and DSOs at the connection point between the main power grid and RESs, which can be referred to as the point of common coupling (PCC) (Battaglini et al., 2009). It requires RESs to act similar to traditional power plants and play an important role in voltage and frequency stability enhancement, withstanding various disturbances and improving the power quality, reliability, and security of the utility grid (Al-Shetwi et al., 2015). The new requirements include voltage regulation, frequency regulation, voltage ride through (VRT) (low voltage ride-through (LVRT), zero-voltage ride through (ZVRT), and high-voltage ride though (HVRT)), power quality standards at the PCC, reactive power injection for the voltage stability support, and active power control for frequency stability support.

The incorporation of wind energy into the grid has accelerated the development of connection requirements and GC improvements. For example, Germany imposed GCs with respect to the high penetration of wind energy in 2008 (Netz, 2008) and other RESs such as PV (Bartels et al., 2008). These requirements have since been often used as a reference for other GCs and the integration of other RESs; GC requirements regarding the penetration of RESs into the national grid have been imposed in several countries, including Spain (García-Sánchez et al., 2014), Italy (CEI-Comitato Elettrotecnico Italiano, 2016), USA (Gevorgian and Booth, 2013), Danmark (de France, 2010), Australia (CommissionNovember 2014), China (GB/T, 2012), Japan (Yang et al., 2015), and Irland (EirGrid, 2015). Other standards, such as the IEEE 1547 standards (Basso and DeBlasio, 2004), which were recently updated in (Committee, 2014), and the European IEC 61727 standards (IEC Standards, 2004; Cleveland, 2008), have also been imposed for distribution systems (RES or non-RES). In comparative studies of GCs, researchers addressed the penetration of the solar PV system regulation such as grid codes for PV power integration standards (Crăciun et al., 2012), and global RESs interconnection standards (Rangarajan et al., 2017), wind system regulations (Mohseni and Islam, 2012), other renewable energies (Rodrigues et al., 2016), and micrograds standards (Basso et al., 2030; Brem et al., 2019; Dragičević et al., 2015). A brief comparison of the new requirements imposed by the USA, Australia, Italy, and Germany to regulate the behavior of voltage and frequency during grid disturbances was also conducted (Al-Shetwi et al., 2015). A comprehensive review, especially concerning European TSOs, federal energy regulatory commission standards in the USA, and operators in Canada and New Zealand, was conducted by Tsili et al. (Tsili and Papathanassiou, 2009). Similarly, researchers have reviewed the technical regulations in German GC, Spanish GC, and the code released by the European TSO regarding the penetration of the PV system into the electrical grid (Shah et al., 2015) and have compared the GC of northern Africa and Spain (Loudiyi et al., 2018/01). A more recent overview of the voltage, frequency, and active and reactive power regulation in the GC of Germany, Romania, the US, China, South Africa, and Puerto Rico has been conducted by (Cabrera-Tobar et al., 2016). There are some review studies that were conducted in the last years concerning RESs integration. For instance, the authors in (Jaalam et al., 2016) presented a review and classification of past studies on synchronization methods for grid-connected RESs converters together with their control and modeling techniques. Performance analysis, design, sizing optimization of stand-alone and grid-connected PV system along with hybrid RESs and utilization of renewable electricity for plug-in electric vehicles in the rural application was reviewed in (Goel and Sharma, 2017). Another review presented in (Thopil et al., 2018) concerning the RES integration into the distribution level of the South Africa electrical grid focusing on its dynamics, availability, cost analysis, and operation optimization. A review of inertia and frequency control strategies in power systems with high RES integration especially wind and PV was conducted in (Fernández-Guillamón et al., 2019). However, the recent integration requirements imposed by different GCs and standards along with compliance technology and controllers not addressed by the aforementioned reviews.

More important than the development of rules and regulations is their application. Compliance verification of the GC requirements should be conducted during the advancement of the integration of RESs. In this context, some researchers have examined the manner in which compliance and verification of the existing technical regulations can be proved. For example, the authors in (Al-Shetwi et al., 2019) performed a comparative study of the VRT regulations in terms of compliance with various GCs. A review on control strategies of distributed generators, including RESs solar, wind, and fuel cell under normal and non-normal operation conditions along with its impact during abnormal grid condition was conducted in (Meral and Çelík, 2019). In Ref (Çelik and Meral, 2019a). the impact of RES based distributed generation systems into electric grid concerning synchronization, control, power management, and power quality problems were discussed. A novel control strategy of a hybrid RES integrated power grid was proposed to maximize power delivery capability, achieve power flow and power-sharing among the different sources, and power management between the electrical grid and load demand (Çelik and Meral, 2019b). Further, a methodology was proposed in a previously conducted study for testing the voltage and frequency regulation compliance according to German GC for a microgrid connected to the main grid (Hirase et al., 2018). A novel control strategy for LVRT in a PV system-connected grid based on the Malaysian GC standards was analyzed by (Al-Shetwi et al., 2018). Similarly, the compliance of a wind farm during grid disturbances with respect to Chinese regulations was investigated by (Liu et al., 2018) and based on the Indian electricity GC by (Priyavarthini et al., 2018). In all the aforementioned studies, some degree of compliance was achieved with respect to the required standards.

As discussed above, there are some review studies of different grid codes, however, as the number and size of RESs are increased, various nations have started to enforce extra and advance requirements while other started to establish its own requirement. Therefore, this study introduces an updated comparison of international GC, standards, rules, and regulations which are officially accepted by the power system operators regarding the integration of RESs in various respective countries to date. Hence, a comparison of the key grid stability requirements with respect to the voltage stability, frequency stability, VRT, power quality issues at the PCC, and active and reactive power regulations are initially addressed. Following that, a deep analysis in terms of the compliance technology, strategies, and controllers that already used to achieve these requirements is highlighted and summarized. The compliance verification is so important to the power system operators to evaluate theses new regulations to ensure the new power sources will not negatively impact the operation and stability of the utility grid. Furthermore, a comparison of the recent integration requirements will assist new power system operators in creating technical regulations according to the regulations existing in countries with high RES penetration levels. This comparative study aims to enable RES developers and manufacturers to attain accurate awareness with respect to the recent international regulations. Finally, suggestions and recommendations for further research from the perspective of engineering applications and academic research are also presented.

2. Surveying methodology

In order to achieve the objectives of this review, the method of the survey was performed on the basis of the content analysis. We searched for literature in the Scopus, Web of Science, Science Direct, Google Scholar databases, research gate, official websites of grid codes for different countries, international agencies such as international energy agency (IEA), and standard such as international electro-technical Commission (IEC), and IEEE standards. In order to look for appropriate articles within the objectives and scope of this review study, the authors used keywords such as renewable energy sources, sustainable power, grid integration, solar energy, wind energy, technical requirements, and renewables control. Many papers from our search have been discovered. By analyzing the title, keywords, abstract, article content and journal's main subject of interest, the relevant literature was chosen. These selected references were read carefully in order to extract the useful information related to the recent integration requirements of RESs into the grid and the compliance technology, strategies, and controllers used to achieve these requirements. The schematic diagram is shown in Fig. 1.

The results achieved were structured into three groups. Firstly, the new RES integration requirements were comprehensively reviewed. The recent integration rules, classifications, characteristics and evaluation processes with advantages and drawbacks were analyzed for all countries' standards across the globe. Next, the state-of-art of the control methods that have been done by the developers and researchers to confirm the compliance with these regulations were discussed and highlighted. These control strategies were classified and then their advantages and limitations are discussed in detail. Finally, based on this review results, an attempt to improve the advanced and recent interconnection requirements in a consistent and harmonized manner was suggested. Moreover, some significant recommendations and suggestions for future improvement on the requirements and control method for reliable and efficient RES integration are provided.

3. Increase in popularity of renewable energy sources

Based on the latest global status report (REN21) of sustainable energy, there was a relatively stable increase in RES power generation in 2018 by 181 GW (GW) when compared with that in 2017; further, the number of nations that have connected high shares of RESs to their grid has continued to increase (Global Status Report, 2019). RESs were expected to account for 26% of the global power generation by the end of 2018 with an expected capacity of approximately 2378 GW. The greatest share of this increase was PV power, accounting for 55% of the newly installed renewable capacity with an increase of approximately 100 GW, followed by wind energy (28%) and hydropower (11%) (Global Status Report, 2019). An overview of the major types of RESs used to generate electricity worldwide is presented in Fig. 2. Renewable power plants (RPPs) currently represent more than a quarter of the world's overall electricity-generating capacity. As of 2017, more than 90 nations had generated at least 1 GW of renewable electricity, whereas at

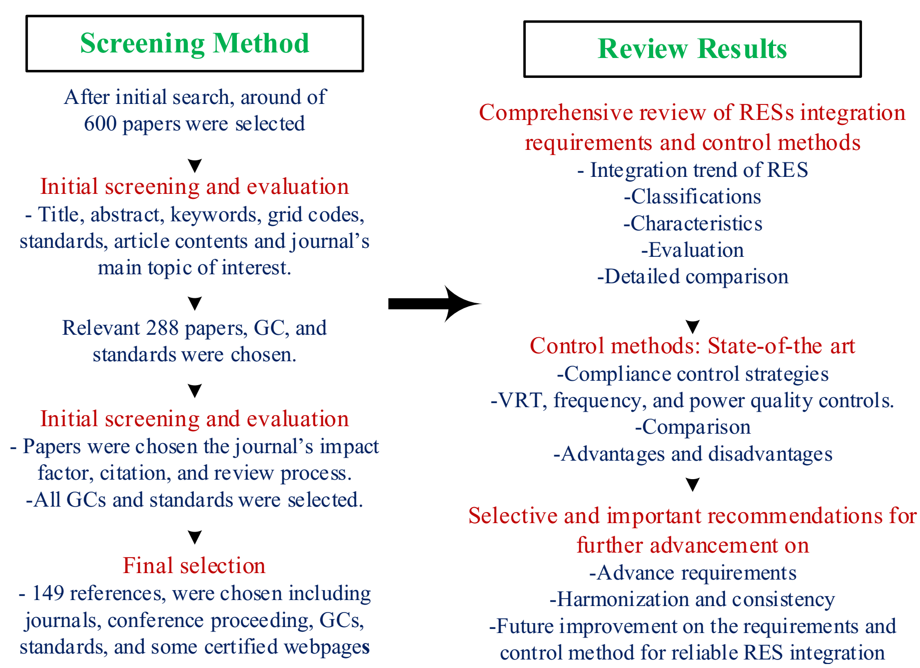

Fig. 1. Schematic diagram of the review.

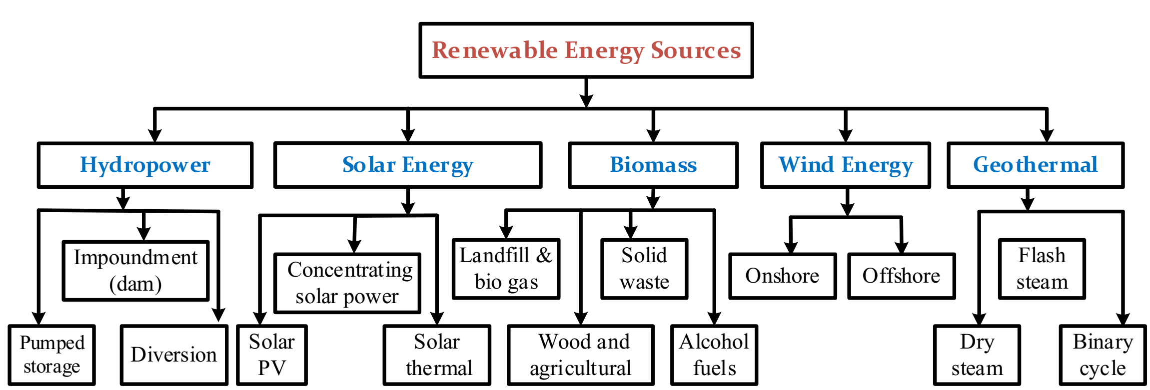

Fig. 2. Overview of the main renewable energy sources.

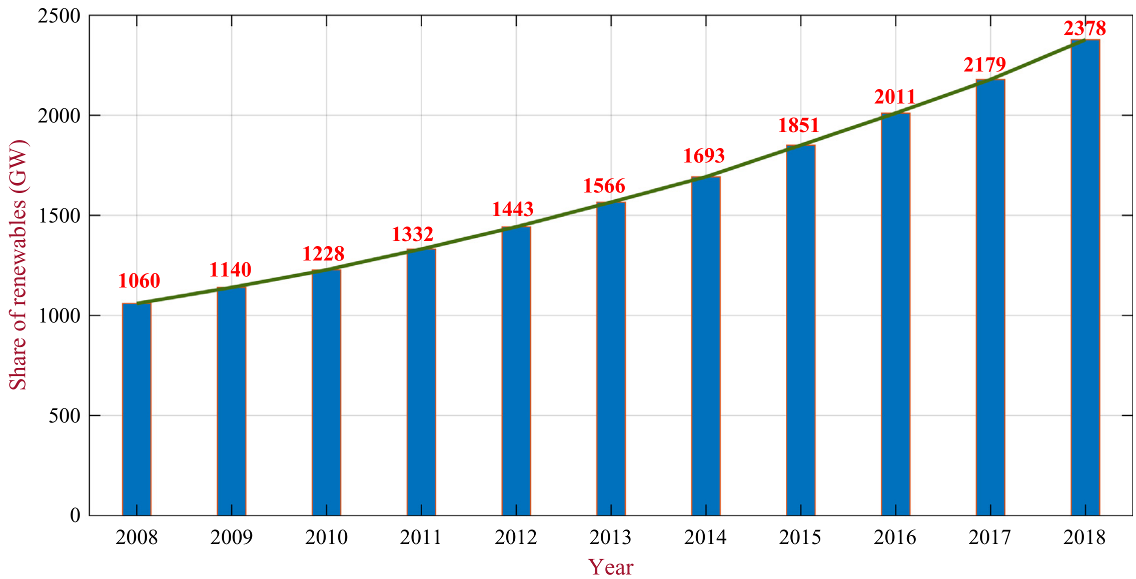

Fig. 3. Global renewable electricity generation in 2008–2018.

least 30 nations had more than 10 GW of generating capacity (Global Status Report, 2019; International Energy Agency (IEA), 2019).

The share of solar PV and wind power further increased in certain areas, and a growing number of nations exhibited more than 20% variable RESs in their electricity generation mechanisms; the global share of RESs from 2008 to 2018 is illustrated in Fig. 3. Additionally, the drastic growth of the share of renewable sources in electricity generation from 2013 to 2018 is presented in Table 1 (Global Status Report, 2019; International Energy Agency (IEA), 2019; International Renewable Energy Agency (IRENA), 2019; Hasan and Dincer, 2019). Overall, solar PV exhibited the highest growth rate from 2013 to 2018, even though hydropower provided the greatest contribution to electricity generation. In 2013, the hydropower capacity was almost double the capacity of all the remaining renewable resources; however, by the end of 2018, the increasing share of other RESs led to a renewable share of hydropower of only 48%. The electricity generation capacity via renewable sources in 2018, excluding hydropower, are shown in Fig. 4 and can be given as follows: wind (591 GW); PV (505 GW); bio-power (130 GW); geothermal (13.3 GW); and others (6 GW). The ten countries with the greatest installed electricity generation capacity via RES in 2018 are summarized in Fig. 5 (Global Status Report, 2019). With the highest share of installed capacity, China accounts for approximately 30% of all installed RESs, followed by the USA, Brazil, and Germany.

Table 1
Electricity generation capacity of renewable sources during 2013–2018.

RES	Total capacity in (GW)					
	2013	2014	2015	2016	2017	2018
Hydropower	1018	1055	1071	1096	1112	1132
Wind	319	370	433	487	540	591
Solar PV	138	177	228	303	405	505
Biopower	88	93	106	112	121	130
Geothermal	12.1	12.9	13	13.5	12.8	13.3
Others	3.9	4.3	4.7	5.1	5.5	6.0
Total without hydropower	560.5	657	785	922	1081	1246
Total with hydropower	1578	1712	1856	2017	2179	2378

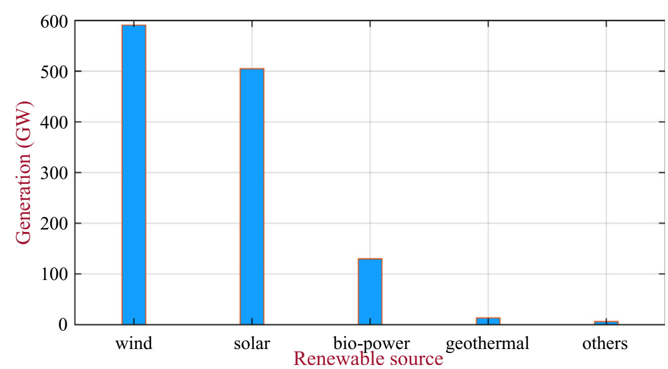

Fig. 4. Capacity of renewable sources (excluding hydropower) in 2018.

4. RES integration requirements

In this section, the developments on recent technical regulations concerning the integration of RESs into the electrical grid to ensure stable power systems are compared. Focus is given to VRT (LVRT, ZVRT, and HVRT) and the injection or absorption of the reactive current, which are important for ensuring voltage support during disturbances and abnormal conditions. The relation between active and reactive power with respect to frequency and voltage stability regulations is discussed based on the recent regulations because some countries and entities have begun imposing regulations to ensure a high quality of power at the PCC to ensure grid stability.

4.1. VRT

One of the most important requirements established due to the high penetration of RPPs, such as wind and PV, into the utility grid is the VRT (Tarafdar Hagh and Khalili, 2019; Döşoğlu, 2016; Ruhang et al., 2018). In the past, the low integration of RESs allowed regulations to require these power sources to directly disconnect from the grid in the event of a fault. However, because RPPs have become

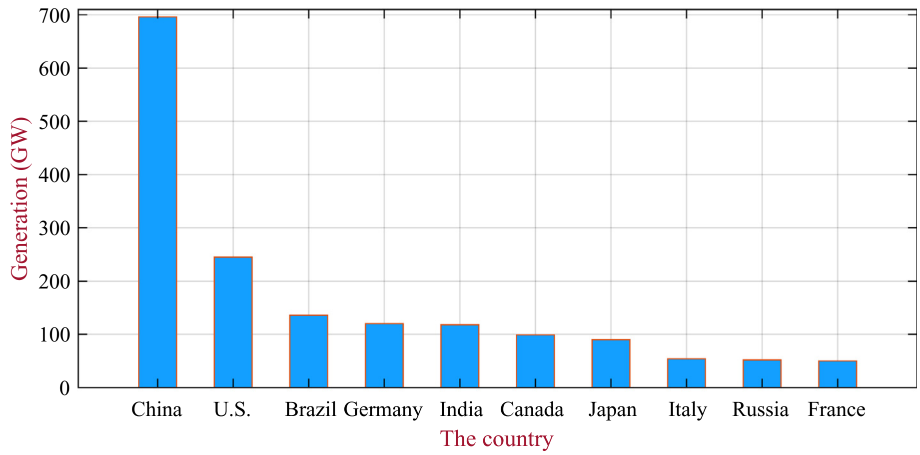

Fig. 5. Capacity of renewable sources (excluding hydropower): Top 10 countries in 2018.

one of the main players in power generation, disconnecting them during faults may aggravate the problem and result in instability. Therefore, most of the current regulations have imposed VRT as a compulsory requirement for any RES connected to the grid (Ayodele et al., 2020). VRT requires the RPPs to act as conventional power plants by staying linked with the grid during faults and by performing auxiliary services (e.g., injection/absorption of the reactive current) to ensure voltage and grid stability.

4.1.1. Low-voltage ride through

Quickly disconnecting an RPP can adversely impact the utility grid stability, particularly in case of large-scale systems. Therefore, regulations that require that the RPP should withstand the fault and remain in operation during a fault that can cause a voltage decrease of less than 90% into a certain percentage of the normal voltage (normally 15%) during a specific period of time have been imposed. After the fault is cleared, the RPP should quickly recover its production of active and reactive power to the pre-fault volume (Meegahapola et al., 2018). An assortment of the LVRT standards of various countries is compared in Table 2 and graphically presented in Fig. 6. The Danish GC (de France, 2010) requires grid-connected wind and PV systems to stay in continuity mode for half a second when the voltage at the PCC drops by 80%. If the voltage at the PCC recovers to become 90% of the original voltage within 1.5 s, the RPP will remain in operation mode without tripping. Otherwise,

Table 2
LVRT parameters in various countries.

Country	*At the time of fault*		*After fault*	
Regulation	$V_{min.}$ (%)	$t_{max.}$ (s)	$V_{max.}$ (%)	t_{max} (s)
Denmark	20	0.5	90	1.5
China	20	0.625	90	2.0
UK	15	0.14	80	1.2
Japan	20	1.0	80	1.2
Romania	15	0.625	90	3.0
U.S.(NERC)	15	0.625	90	3.0
U.S.(PREPA)	15	0.60	85	3.0

Table 3
ZVRT parameters in various countries.

Country	*At the time of fault*		*After Fault*	
Regulation	$V_{min.}$ (%)	$t_{max.}$ (s)	$V_{max.}$ (%)	t_{max} (s)
Germany	0	0.15	90	1.5
Canada	0	0.15	85	1.0
Australia	0	0.45	80	0.45
Spain	0	0.15	85	1.0
Italy	0	0.2	85	1.5
South Africa	0	0.15	85	2.0
Malaysia	0	0.15	90	1.5
U.S. (WECC)	0	0.15	90	1.75

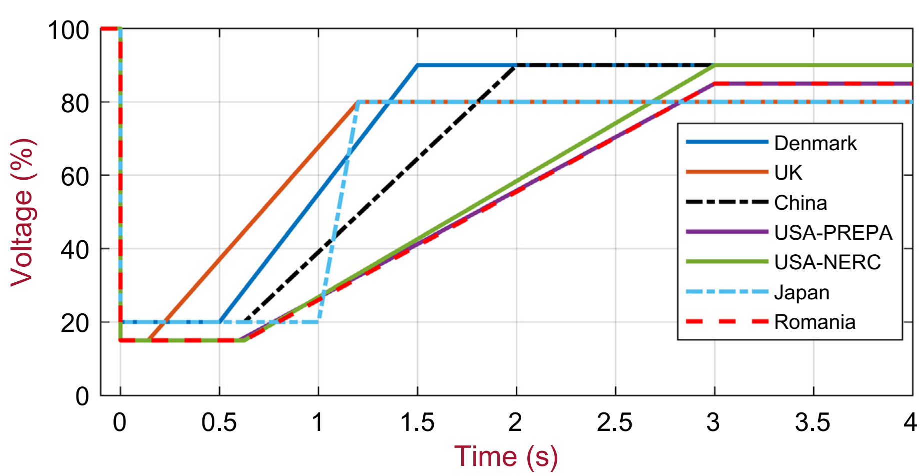

Fig. 6. LVRT requirements in various countries.

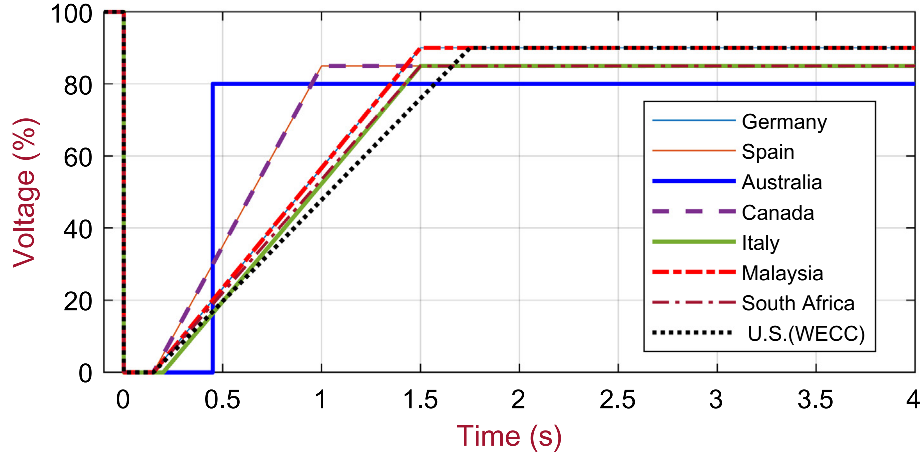

Fig. 7. ZVRT requirements in various countries.

Table 4
HVRT parameters in various countries.

Country	*During Fault (caused voltage increase)*	
Regulation	V_{max}. (%)	$t_{max.}$ (s)
Germany	120	0.1
Denmark	120	0.1
Spain	130	0.25
USA−PREPA	140	1.0
USA−(WECC)	120	1.0
USA−NERC	120	1.0
Italy	125	0.1
Australia	130	0.06
South Africa	120	0.15
Malaysia	120	Continuous
China, UK, Japan, Canada, and Romania	ND	ND

*ND: HVRT regulations are not defined as compulsory.

disconnection is compulsory. The remaining LVRT requirements are similar to the Danish requirements with a slight difference observed with respect to the time period and voltage levels. According to the regulations in Denmark, China, and Japan, if the voltage drops 80% below its nominal value, the RPP should withstand the fault and remain connected to the grid for a particular time; otherwise, it must be rapidly disconnected. Similar requirements have been imposed in the UK, Romania, the North American electric reliability Corporation (NERC), and the Puerto Rico electric power authority (PREPA) in the USA, where RPP is required to maintain connection mode even though the voltage drops to 15% from the normal value.

4.1.2. Zero-voltage ride through

ZVRT can be considered to be a special case of LVRT because ZVRT represents an extreme case in which the voltage decreases to become zero; thus, the RES can stay in connection mode and support the grid for a specific period of time (Zhang et al., 2017). As with LVRT, the RESs should support voltage recovery and grid stability through reactive current injection during zero-voltage situations (Sutherland, 2015). A summary of the ZVRT parameters required in various countries are summarized in Table 3 and Fig. 7. All the examined regulations have banned disconnection from the grid during voltage sag even when the voltage decreases to zero. However, the recovery voltage values (V_{max}) and times are mostly different. In all the cases, ZVRT should be applied at the PCC (Al-Shetwi and Sujod, 2018c).

4.1.3. High-voltage ride through

Because a voltage swell can cause overvoltage in the power grid and lead to voltage instability, recent integration requirements require RPPs to remain associated with the utility grid once the voltage increases for a specific period of time to maintain voltage stability and evade critical incidents resulting from overvoltage.

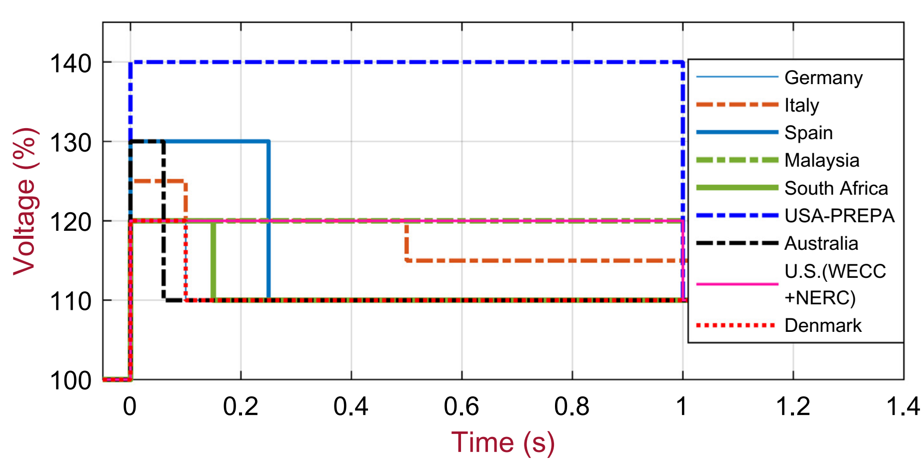

Fig. 8. HVRT requirements in various countries.

These requirements, known as the HVRT requirements, are summarized and compared by country in Table 4 and Fig. 8 (Liu et al., 2019). Table 4 presents and compares the HVRT regulations enforced by different countries and the GC requirements. Although voltage swell incidents (i.e., over-voltage) occur less frequently, they have been regulated in a similar manner to voltage sag (i.e., under-voltage) incidents (Haidar and Julai, 2019/06). However, some countries (such as China, Japan, Canada, and Romania) that enforce LVRT for any renewable generator have not imposed similar HVRT requirements. Fig. 8 compares the state-of-the-art HVRT imposed by Germany, Denmark, Spain, USA, Italy, Australia, South Africa, and Malaysia. The regulations imposed by PREPA in the USA are the most stringent, requiring the renewable generators to stay connected and resist an overvoltage of up to 140% of their original value within 1 s (Gevorgian and Booth, 2013). They have been followed by Spain (García-Sánchez et al., 2014) and Australia (CommissionNovember 2014), which allow an overvoltage of up to 130% from the nominal value before disconnection from the grid.

Overall, based on the comparison provided above, it is hard to find a uniform VRT requirements globally, because of the different levels of renewable energy penetration into the main grid and different operational methodologies of the national grids.

4.2. Reactive current injection/absorption

Most of the GCs require RPPs to withstand faults and stay connected as well as operate similarly to traditional synchronous generators. Therefore, reactive currents have to be injected into the main grid to assist voltage recovery and sustain the stability of the power system (Oon et al., 2018). This support via reactive current must be performed concurrently with LVRT/ZVRT for the period of occurrence of under-voltage (inductive loads) to reduce the voltage drop and speed up voltage recovery during and after a fault, respectively. In the case of an over-voltage, the renewable generators must absorb reactive current during HVRT to preserve voltage stability (Etxegarai et al., 2015).

The amount of absorbed or injected reactive current should be evaluated according to the voltage drop or increase, respectively. Thus, the amount of reactive current during grid disturbances should be presented according to the curve shown in Fig. 9, as imposed by the German GC requirements (Netz, 2008; Bartels et al., 2008). If the voltage decreases or increases within the dead-band (±10%), the RPPs must maintain normal operation, and no reactive current action can be performed. Once the voltage increase or decrease surpasses the dead-band, the RESs must be injected with the reactive current to the grid by fulfilling the slope (red line) that can be defined as droop (k) in which $k \leq 2$ *p.u.* If the voltage becomes less than 50% of the nominal value, the reactive current must be injected into the grid with at least 100% of its rated value that can be calculated as follows:

$$I_q \geq k(1 - V_g), \quad (1)$$

where V_g represents the terminal voltage of the RES (x-axis), the reactive current is represented by I_q (y-axis), and the slope $k = 2$. The USA–PREPA standards require RESs, especially wind and PV plants, to inject/absorb 1%–10% of the reactive current if the voltage exceeds the ±15% dead-band (Gevorgian and Booth, 2013). Based on the Australian regulations, as the voltage drops 1% from its nominal value, the RES must inject reactive current at 4% from its rated value (CommissionNovember 2014).

4.3. Frequency stability regulations and active power control

To maintain a stable frequency in the electrical grid (typically 50 or 60 Hz), the active power output must become equal to the load demand at any given time because any imbalance between electricity generation and demand causes the frequency to deviate from its typical value. Thus, conventional power plants (i.e., thermal fossil-based plants) are usually equipped with governor control, which is activated during an imbalance; the governor control serves as primary load control and prevents a large frequency deviation (Dreidy et al., 2017; Sedighizadeh et al., 2019). However, the RPP generation units do not have direct governor control to deal with frequency variation. Because the RPPs have replaced traditional plants, alternative frequency stability methods have attracted attention (Stram, 2016). Therefore, international GCs require that RPPs should have methods to manage their active power yield with respect to the frequency variations. According to a typical active power and frequency variation curve, as depicted in Fig. 10 (Al-Shetwi and Sujod, 2018c), as the frequency increases, the generated active power should be reduced. For example, the German GC requires that the active power output must be minimized to a rate of 40% when the frequency varies between 50.2 Hz and 51.5 Hz, based on Eq. (2). However, if the frequency becomes lower than 50.2 Hz, the generation units need to return active

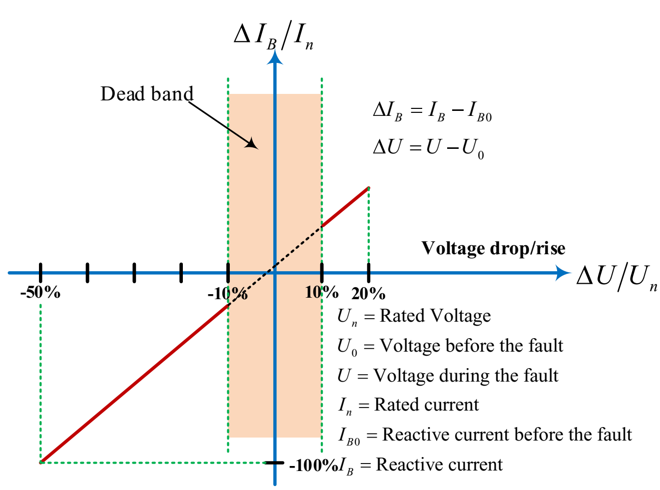

Fig. 9. The amount of required reactive current to support the voltage during faults (Biswas et al., 2017a).

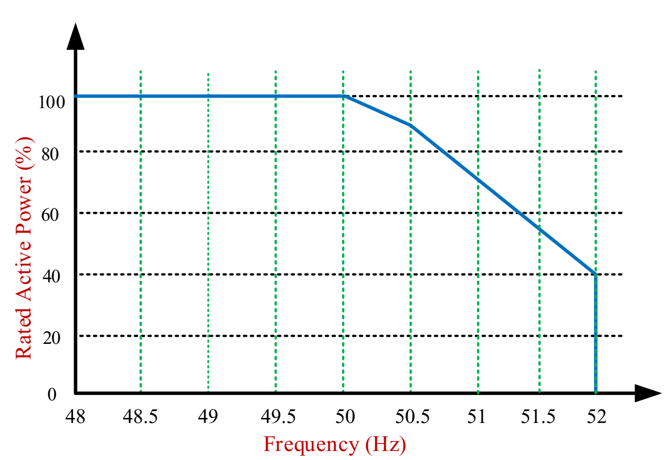

Fig. 10. Typical active power–frequency response (Al-Shetwi et al., 2015).

Table 5
Normal operation frequency limits in various countries.

Country	Typical Frequency (Hz)	limits of Frequency (Hz)
Germany	50	$47.5 < f < 51.5$
Denmark	50	$48.5 < f < 51$
Spain	50	$47.5 < f < 51.5$
Canada	60	$59.4 < f < 60.6$
China	50	$49.5 < f < 50.2$
USA–PREPA	60	$57.5 < f < 61.5$
USA–NERC	60	$58.5 < f \leq 61$
East of Japan	50	$47.5 < f < 51.5$
West of Japan	60	$58 < f < 61.8$
Australia	50	$47.5 < f < 52$
South Africa	50	$49 < f < 51$
Malaysia	50	$47 < f < 52$
Ireland	50	$49.5 < f < 50.5$
Romania	50	$47.5 < f < 52$
UK	50	$47.5 < f < 52.0$

power to its rated value. If the frequency becomes greater than 51.5 Hz or lower than 47.5 Hz, fast disconnection is required (Netz, 2008; Bartels et al., 2008).

$$\Delta P = 20 \times P_m \times \frac{50.2Hz - f_{grid}}{f_{grid}} \quad at\ 50.2 \leq f_{grid} \leq 51.5 \tag{2}$$

Here, f_{grid} denotes the network frequency, ΔP represents the amount of power reduction, and P_m denotes the instantaneous available power. The Irish GC requires RESs to decrease the generated power once the frequency varies outside of $49.7 < f < 50.3$ Hz; otherwise, normal operation will continue (EirGrid, 2015). The Malaysian GC requires the PV power plants to reduce the output power with a gradient of 40% per Hz if the frequency becomes greater than 50.5 Hz (Energy Commission Malaysia (ECM), 2017). Some countries have no defined frequency support regulation, whereas others, such as South Africa, left this issue to the TSO or DSO (Sewchurran and Davidson, 2016). China's GC does not require active power reduction once the frequency increases; however, the RPPs must withstand a frequency variation between 50.2 Hz and 50.5 Hz or disconnect from the grid (GB/T, 2012). Table 5 presents the allowed frequency variation range under which the RPPs should stay in normal operation without any active power reduction in different countries.

4.4. Voltage regulation and reactive power control

Typically, synchronous generators and distribution substations are tasked with overcoming the voltage deviation at the transmission and distribution levels, respectively. However, high RES penetration can considerably affect voltage stability and increase the difficulty of these tasks (Hossain and Pota, 2014). Therefore, power system operators have been challenged with how to maintain stable voltages within safe limits under different operating situations. One solution involves the regulation of the power factor at the PCC using either the active power or terminal voltage; the typical requirements of power factor regulation based on the active power and terminal voltage to support the grid stability are presented in Fig. 11(a) and (b), respectively (Tsili and Papathanassiou, 2009; Sourkounis and Tourou, 2013).

Based on the German requirements, any PV or wind power plant connected a low voltage network has to provide reactive power outside 0.95 leading/lagging power factor (Netz, 2008; Espinoza et al., 2013). The same requirements have been imposed in Italy, China, and South Africa. The Irish standards require wind power plants to operate with a leading/lagging power factor of 0.835 (EirGrid, 2015; Singh and Singh, 2009). The Malaysian standards require reactive power support for PV systems at the PCC to ensure that the power factor is within 0.9 leading/lagging (Energy Commission Malaysia (ECM), 2017). The Spanish GC establishes that the PV systems must work with a minimum power factor of 0.85 leading/lagging and that the wind farms should operate within a 0.91 leading/lagging power factor (Mohseni and Islam, 2012; Morales et al., 2008). Therefore, some networks are required to keep the voltage stable within acceptable limits (normally 0.9 to 1.1 p.u); otherwise, reactive power support through power factor regulation must be applied at the interconnection point.

4.5. Power quality requirements

The large-scale integration of RESs may result in power quality issues (Liang, 2016). Therefore, standards and regulations have been enforced in various countries to ensure a good quality of power from RESs. The main power quality concerns associated with RES integration are voltage transients, harmonics, flickers, and voltage unbalance (Anees, 2012). Therefore, this section focuses on the requirements that have been imposed to stabilize the harmonics, flickers, and voltage unbalances concerning RES integration.

4.5.1. Harmonics

Harmonic distortion is a serious power quality problem in which there is a distortion in the current or voltage waveform that causes it to change from its normal characteristics or shape. One of the main sources of this distortion at the generation level is the usage of power electronic devices; RESs use several power electronic devices that produce this distortion (Jaalam et al., 2016/06). Therefore, strict regulations have been issued to ensure a low level of harmonic distortion caused by RESs at the PCC. The power quality is

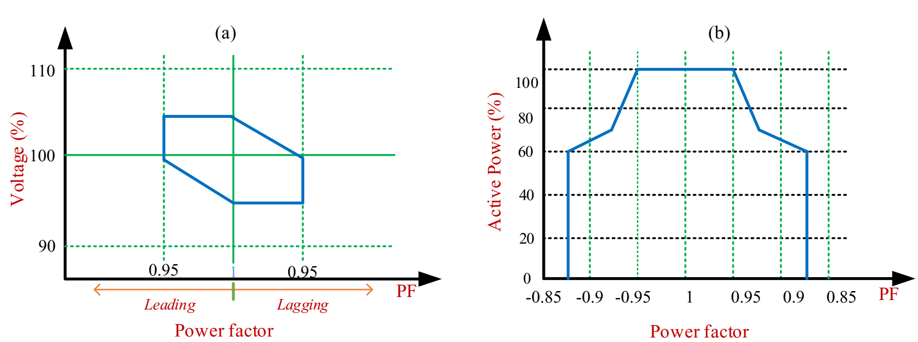

Fig. 11. Typical power factor deviation range with regard to the (a) terminal voltage and (b) active power.

Table 6
Current harmonics distortion limits in different standards.

The standards	Type	Harmonic order	Distortion limit	THD (%)
IEEE 929, IEEE 1547 AS 4777.2 (Australia), GB/T (China), and ECM (Malaysia)	odd	33 < h	ND	<5%
		23 ≤ h ≤ 33	<0.6%	
		17 ≤ h ≤ 21	<1.5%	
		11 ≤ h ≤ 15	<2%	
		3 ≤ h ≤ 9	<4%	
	Even	10 ≤ h ≤ 32	<0.5%	
		2 ≤ h ≤ 8	<1%	
UK (EREC G83 Stds.)	odd	h = 3, 5, and 7	<(2.3, 1.14, & 0.77)%	<3%
		h = 9, 11, and 13	< (0.4, 0.33, & 0.21)%	
		11 ≤ h ≤ 15	<0.15%	
	Even	h = 2, 4, and 6	<(1.08, 0.43, &0.3)%	
		8 ≤ h ≤ 40	<0.23%	
Canada (CAN/CSA C22.3 Stds.)	odd	33 < h	<0.33%	<5%
		23 ≤ h ≤ 33	<0.6%	
		17 ≤ h ≤ 21	<1.5%	
		11 ≤ h ≤ 15	<2%	
		3 ≤ h ≤ 9	<4%	
	Even	34 < h	<1.0%	
		22 ≤ h ≤ 32	<0.5%	
		16 ≤ h ≤ 20	<0.4%	
		10 ≤ h ≤ 14	<0.2%	
		8 ≤ h ≤ 40	<0.1%	
IEC 61000-3-2	odd	h = 3, 5, and 7	<(3.45, 1.71, & 1.15)%	<5%
		h = 9, 11, and 13	<(0.6, 0.5, & 0.3)%	
		15 ≤ h ≤ 39	<0.225%	
	Even	h = 2, 4, and 6	<(1.6, 0.65, &0.45)%	
		8 ≤ h ≤ 40	<0.345%	

commonly measured using the voltage and current total harmonic distortion (THD) and can be defined as follows (Memon et al., 2018; Jannesar et al., 2019):

$$THD = \frac{\sqrt{\sum_{n=2}^{k} h_n^2}}{h_1}, \tag{3}$$

where h_1 is the fundamental component, $h_2 \ldots .h_n$ are the harmonic effective values from order 2 to k, and k and n represent the last harmonics series and harmonics order, respectively (Memon et al., 2018). To ensure that the voltage and current waveforms are synchronized with the grid, some requirements have been imposed with respect to the THD limits for renewable sources connected to the grid. For example, IEEE Std 519-201, IEEE 1547 Stds, and IEC standards (Committee, 2014; Cleveland, 2008; Cho et al., 2019) require the voltage and current THD to be lower than 5% at the PCC. Some countries' standards, including the Brazilian ABNT 16149 (Figueira et al., 2015) and Malaysian technical regulations (Energy Commission Malaysia (ECM), 2017), require the THD to not exceed 5% at the transmission or distribution connection point. Romanian standards require a THD of a maximum of 3% for PV and wind plants integrated with the transmission system (Regulatory Authority for Energy, 2014). Overall, the majority of the countries follow either the IEEE or IEC standards (Gao et al., 2016), excluding EREC G83 which is notably strict. The current harmonics distortion limits according to different standards are listed harmonics Table 6.

4.5.2. Voltage unbalance

A voltage unbalance occurs when the three-phase voltage differs in magnitude or in a nominal phase shift (120°) and can be calculated as the ratio of the positive to negative sequence voltage component (Shang et al., 2019). The quality of voltage unbalance is monitored in several standards using the voltage unbalance factor (VUF), which can be given as follows (Kim, 2018; Neukirchner et al., 2017):

$$VUF = \frac{V^+}{V^-} \times 100\%, \tag{4}$$

where V^+ and V^- are the positive and negative voltage sequences, respectively. Because voltage unbalance is a good indicator of the power quality delivered to the grid, some standards and GCs limit the VUF at the PCC and ensure that a balanced three-phase voltage is injected into the grid. For example, IEEE Std. (Committee, 2014) requires the voltage unbalance to not exceed 3%, whereas the IEC standards require all the distribution generators to maintain a VUF of lower than 2% (Cleveland, 2008). Romanian standards imposed a voltage unbalance of 1% at the interconnection point of both the PV and wind plants (Regulatory Authority for Energy, 2014). The UK recommendation (P29), also followed by Malaysia, stated that the voltage unbalance of the grid shall not exceed 2% at the PCC or 1.3% at the load (Energy Commission Malaysia (ECM), 2017). In Canada, the CAN/CSA-C61000-2-2 standard stated a maximum voltage unbalance of 2% (Papachristou et al., 2018). Overall, the standards around the world have identified the suitable limit of voltage unbalance to be between 1% and 2% (Ghassemi and Perry, 2014).

Table 7
Flicker limits at different voltage levels based on different standards.

Standard	Voltage level	P_{lt}	P_{st}
IEEE Std. 519	MV	0.7	0.9
	HV–EHV	0.6	0.8
China	MV–HV	0.7	ND
IEC61000	MV	0.8	1
Malaysia	LV (less than 11 kV)	0.8	1
	MV (11–33) kV	0.7	0.9
	HV (above 33 kV)	0.6	0.8
USA	LV	0.7	0.9
	MV–HV	0.6	0.8
Brazil	LV–MV	0.8	1

4.5.3. Flicker

The power output from RES is highly intermittent, hence producing an enormous amount of voltage fluctuations and flickers on the distribution networks which gain more concern recently. Rapid changes in load can cause fluctuation in a customer's voltage; this fluctuation in voltage can be referred to as voltage flicker and is an irritation issue that can be noticed in the form of illumination changes (Commission, 1997; O'Driscoll and O'Donnell, 2013). Flicker is measured based on the short-term (P_{st}) and long-term (P_{lt}) probabilities of occurrence, where $P_{st} = 0$ indicates no voltage flicker and the flicker pollution is defined as $P_{st} = 1$. IEC standard 61000-4-15 has defined the measuring time for P_{st} and P_{lt} as at least 10 min and 2 h, respectively (Silsüpür and Türkay, 2015). The acceptable flicker level for medium-voltage or small- and medium-scale renewable generators has generally been regarded as 1.0 and 0.25 for P_{st} and P_{lt}, respectively (Macii and Petri, 2020). A summary of the specified flicker limits is presented in Table 7 (Energy Commission Malaysia (ECM), 2017).

5. Compliance and control methods

As the RES penetration level has continued to increase, various conditions, including the management and verification of voltage transience, voltage reduction, sag, swell, reactive current injection/absorption, grid support during disturbances, active and reactive power control, power quality issues, voltage variance, and frequency toward grid stability, have been imposed to require RPPs to act like traditional power plants. Accordingly, developers, manufacturers, and researchers must be able to confirm their compliance with these regulations via control methods. The two strategies used to perform compliance verification, including simulation and practical tests, are discussed in this section because they can be applied to the verification of some compliance controls and solutions to achieve the recent requirements from RPPs.

5.1. Voltage ride through and reactive current support

As the reactive current support must be performed during the LVRT/ZVRT (injection) and HVRT (absorbing) period, many control strategies have been adapted to achieve VRT and reactive current support for different RESs. These strategies can be categorized into enhanced and external-device-based controllers, as summarized in Fig. 12. For instance, external devices, such as energy storage systems (ESSs), have been proposed to consider LVRT standards concerning PV integration using supercapacitors (Mohammadi et al., 2018) and batteries (Manikanta et al., 2017; Jaalam et al., 2017) energy storage. Similarly, LVRT compliance regarding wind farm penetration has been studied using supercapacitors (Döşoğlu and Arsoy, 2016) and batteries (Shen et al., 2015). In case of a fault, an ESS controller can withstand the fault, absorb excess energy, and inject reactive current to fulfill the LVRT/ZVRT requirement to ensure grid stability. After the fault is cleared, the stored power can then be fed to the grid. However, ESSs have high initial and maintenance costs. Additionally, the HVRT requirements have not been yet been addressed using ESSs. Some researchers have investigated the VRT and reactive current support with respect to biomass integration using external devices such as a series braking resistor (SBR); their results indicated that SBRs have the ability to fulfill these requirements (LI et al., 2017).

A methodology for achieving the LVRT and HVRT requirements along with the absorption or injection of reactive current during sag or swell events, respectively, for the wind farms connected to the main power grid is proposed by (Liasi et al., 2018) using the enhanced control methods based on German GCs. The authors used a fuzzy controller (optimized controller) to withstand grid faults and support voltage recovery by reactive current injection in compliance with the German standards. External devices have also been used to attain VRT and reactive current support for grid-connected PV systems such as a static synchronous compensator (STATCOM) (Popavath and Kaliannan, 2018), a static var compensator (SVC) (Ayvaz and Özdemir, 2016), and a brake chopper circuit (BCC) (Al-Shetwi and Sujod, 2018a). Similarly, STATCOM (Dey et al., 2018), series dynamic breaking resistor (SDBR) (Hossain and Ali, 2014), and SVC (Rezaie and Kazemi-Rahbar, 2019) have also been investigated for the integration of wind farms. Among these, BCC can withstand grid faults but cannot attain current injections as STATCOM or SVC have done. An improved inverter controller was introduced to satisfy the Malaysian requirements (Al-Shetwi et al., 2018). The effectiveness of the model predictive controller to enhance the VRT is investigated in (Zangeneh Bighash et al., 2018/06). The HVRT requirements, as stated by Chinese GC, have been fulfilled in (Fan et al., 2017). In the case of overvoltage, the proposed HVRT controller restricts the voltage within the required ranges by absorbing a specific amount of reactive power.

Other enhanced controllers include a ZVRT control strategy that depends on a second-order generalized integrator technique to satisfy the Italian GC requirements for single-stage PV systems to face extreme grid faults (Zhang et al., 2017). In case of the ZVRT events, the injected reactive current was at least 100% of the nominal value, as depicted in Fig. 13, because ZVRT is caused by an extreme grid fault that causes the nominal voltage to decrease to zero. A novel controller-based dynamic voltage support uses a hybrid system comprising external devices represented as a dynamic voltage restorer (DVR) and optimization control represented as a multi-objective bee algorithm to achieve LVRT/HVRT with injection/absorption of reactive current for a large-scale wind-farm-connected grid (Falehi and Rafiee, 2018). It is important mentioning that, for more efficient LVRT during unbalanced grid faults, the current limitation control and active and reactive power regulation with fewer oscillations are important. In this regard, a reference current generator based flexible power control strategy is presented in (Çelík and Meral, 2019). The results of this study show the

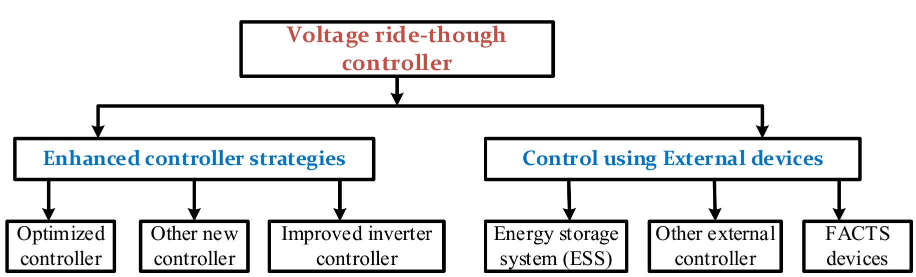

Fig. 12. Classification of the voltage ride through controller types.

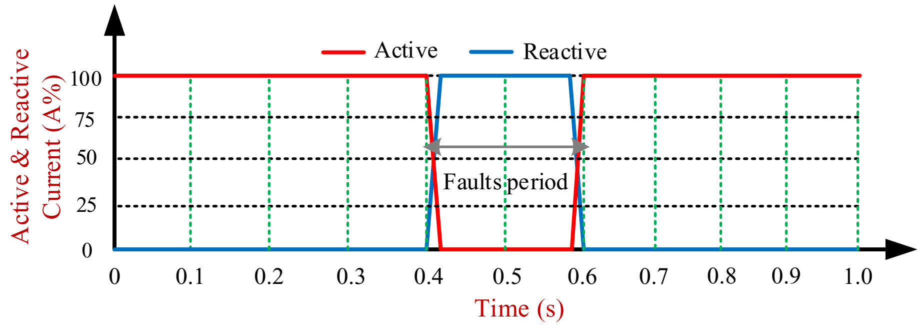

Fig. 13. Injected reactive current during ZVRT situation.

effectiveness of the proposed control to regulate active and reactive power and reduce their oscillations under grid faults. Overall, many researchers have investigated how to fulfill the new integration requirements, and a majority of these studies exhibit excellent performance and conclude that the VRT and reactive current support are important features that allow RPPs to behave similarly to conventional power plants, contributing to grid security and stability.

5.2. Frequency stability regulations and active power control

The response of RESs to grid frequency variation has been thoroughly investigated in recent years. A literature survey indicates consensus on the importance of frequency stability requirements through active power control with respect to the integration of RESs (Dreidy et al., 2017; Mirhosseini, 2019). Frequency stability methods via active power control have been developed for PV systems and wind turbines. For example, fuzzy-gain-scheduled PI control and adaptive pole placement control methods are used to control the amount of active power delivered to the grid during frequency variations for large-scale wind farms (Badihi et al., 2015/01). The authors in (Luo et al., 2019) introduced an automatic generation control method to reduce the active power generated from a wind farm when the frequency began to increase. A closed-loop active power control method proposed by (Chen et al., 2019/05) aimed to develop a dynamic frequency response in a wind-farm-connected grid. An active power tracking model was subsequently used to reduce generated power. A control method for modifying the amount of active power production in terms of frequency variation was proposed for PV systems by (Bullich-Massagué et al., 2017/03). Their results indicated the effectiveness of the proposed controller by storing excessive power in the battery energy storage system during an increase in frequency until a stable status is achieved. An additional active power control loop has also been applied to evaluate the impact of large-scale PV systems on the frequency response under disturbances based on the USA standards (Liu et al., 2016). Overall, the application of frequency requirements via active power integration has been shown to improve frequency stability and allow RESs to actively contribute to grid stability.

5.3. Voltage stability regulation and reactive power control

Large-scale RPPs are commonly located in large deserts or other open areas, which normally exhibit low load demand; the generated power must be exported to the surrounding areas. At the connection point between the RPPs and the main grid, the reactive power balance of the grid may be disturbed, causing the voltage bus-bars to fluctuate because of the variable power generation of RESs. In the meantime, the poor support of the reactive power of the remaining RPPs could result in voltage instability (Bozalakov et al., 2019; Mararakanye and Bekker, 2019; Dike and Mahajan, 2015). Therefore, inverter controllers have been developed for PV systems to regulate their reactive power control. For example (Zhou and Chao, 2013), used an inverter control method to regulate reactive and active power in an independent manner to grant grid

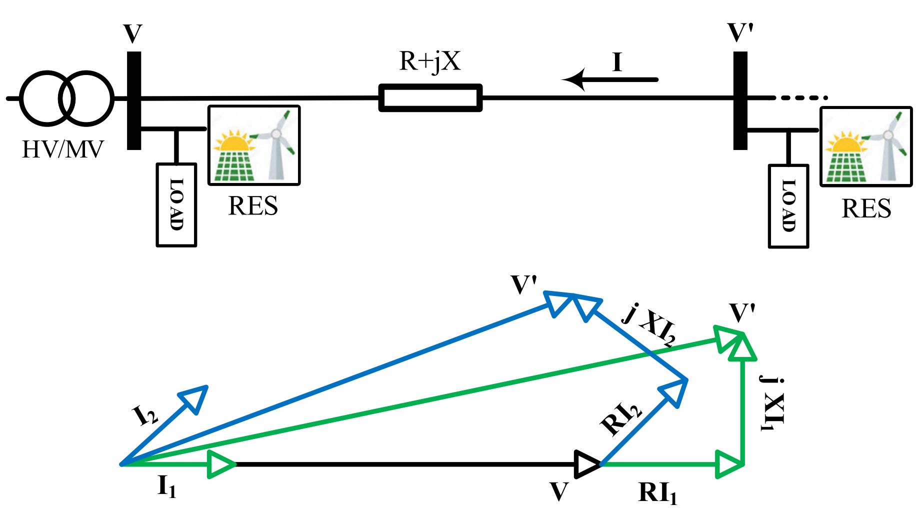

Fig. 14. Mitigation of the voltage instability via reactive power control.

voltage stability based on the recent requirements. Similarly, reactive power control improvements that were compatible with German GCs were also investigated (Bae et al., 2013). Researchers have also indicated that P–Q control can be used to control reactive power with high accuracy in accordance with the GC regulations (Adhikari and Li, 2014). Reactive power control was introduced by (Darwish et al., 2017) in response to high PV penetration into the Egyptian grid to enhance voltage stability using real data obtained from the local grid. For the wind and PV plants, if the voltage limits exceed 1.1 p.u., the inverter should absorb reactive power and mitigate the incidence of overvoltage. As illustrated in Fig. 14, when the voltage is in phase with the current (i.e., the green lines), overvoltage occurs because of feeder impedance. Regardless, the leading current (i.e., the blue lines) can significantly reduce the voltage on the other bus. Thus, the inverter must accordingly absorb the reactive current (Mirhassani et al., 2015).

Other devices used for reactive power support for PV or wind integration, such as SVC, capacitor banks, or STATCOM, have been used to support the voltage via reactive power control (Gasperic and Mihalic, 2019; Yahyaoui, 2018). In case of hydropower, reactive power control has been introduced for use with hydropower integration to support the stability of the weak power systems (Hasanova, 2018) and to satisfy the Romanian grid stability requirements (Năstase et al., 2017). Reactive power control was also introduced by (Xiao et al., 2014) to improve the voltage response considering the daily stochastic nature of electricity generation. Overall, reactive power control for a renewable-connected grid is an essential factor for achieving voltage stability under several operating conditions.

5.4. Compliance with the power quality requirements

Over the previous two decades, investigation of the power quality has increased due to the increasing occurrence of power quality issues generally caused by the proliferation of highly sensitive electronic equipment (Hossain et al., 2018). Thus, several standards and regulations have aimed to enhance the quality of the output power of RPPs to the electric grid and improve the overall system quality. Power quality issues concerning the penetration of RESs, such as harmonics, voltage unbalance, and voltage flicker, has been recently analyzed to fulfill the standard requirements. For example, an analysis of the voltage unbalance and harmonics mitigation of large-scale solar power plants connected to the Malaysian grid indicated that the voltage unbalance, voltage THD, and current THD could decrease to 0.2, 0.74%, and 0.15%, from 2, 9.3%, and 2.8% respectively, satisfying the national GC requirements (Al-Shetwi and Sujod, 2018b). A method for mitigating the flicker emissions in a weak distribution network containing an integrated wind power system was proposed that depended on the change in the generator speed and stored the three-phase oscillation in the turbine shaft inertia (Ayvaz and Özdemir, 2016). Furthermore, flicker reduction was obtained based on the perfect grid impedance angle to omit voltage fluctuations. Similarly, a controller integrated with the main grid was presented in (Girbau-Llistuella et al., 2014) to reduce the voltage flicker of wind turbines within the specified limits. The power quality of a PV system integrated with the distribution system in the tropical area was analyzed by recording the voltage unbalance, flicker current, and voltage harmonics at the PCC between the PV station and the Colombian grid (Granja et al., 2018). Here, a 3.5% increase in voltage unbalances and 22% and 7% increases in current and voltage harmonics were observed, respectively. The voltage flicker short-term (P_{st}) and long-term (P_{lt}) probabilities ranged from 0.2 to 0.35 and from 0.09 to 0.10, respectively, both of which were within the specified range. This study concluded that connecting RESs to old and low-voltage grids can cause several quality issues.

Arshard et al. (Arshad and Lehtonen, 2019) proposed a comprehensive flicker control method for grid-connected PV systems that effectively and quickly eliminated voltage fluctuation and reduced the flicker at the PCC to fall within the defined standards. A methodology to mitigate the harmonics, voltage flicker, and unbalance of a PV system at the PCC was also introduced by (Hernández et al., 2011) to satisfy the IEEE standards. An active shunt filter was used for wind farms in (Zahira et al., 2016), and a controller of the modular multilevel converters was equipped with a large-scale wind farm in (Fey et al., 2017) to maintain the THD levels within the standard limits. The voltage unbalance of grid-connected wind turbines was ensured to be in compliance with the USA standards by injecting negative sequences of current using DVR into the grid to decrease the VUF at the PCC (Suppioni et al.,

Table 8
Different control methods applied to achieve the standards and grid codes requirements.

The requirement	Method	Ref.	Fulfillment of the standards	Limitation of the method.
LVRT	Energy Storage system controller	Ota et al. (2016)	Grid is supported by reactive power, as stated by GCs.	-Caused high fluctuation and overshooting. -High investment price and short lifetime. -Require regular inspection and maintenance.
LVRT	STATCOM & SVC	(Popavath and Kaliannan, 2018; Castilla et al., 2014)	Inject reactive currents and enhance VRT capability.	-Increase the complexity and cost. -Did not address the increasing of dc-link voltage during grid faults. -Do not deal with inverter protection.
Frequency variation	Active power control	(Bullich-Massagué et al., 2017/03)	Kept the frequency with the limits ($49 \leq 50 \leq 51$)	-Only one type of fault is tested. -No sever disturbances are tested.
VRT	Modified inverter controller	Al-Shetwi et al. (2018)	Achieved the VRT, as stated in GC.	-More complex. -Extra hardware for dc voltage protection.
Voltage harmonics	New inverter Configuration	Bhukya et al. (2019)	3.24% (within limits).	-A large number of components. -The inverter controller becomes more complex.
Current harmonics	Active power filter	Colque et al. (2018)	3.46% (within limits).	-Difficulties in keeping voltages constant on the dc-link capacitor.
Flicker problem	Novel estimation method	Rahman et al. (2018)	Pst = 0.72 (within limits). Plt = 0.16 (within limits).	-ND.
Voltage Unbalance	Dynamic voltage stability control strategy	Islam et al. (2019b)	VUF% = 2.85 case 3 (Exceed the limits stated by some standards).	-Exceed the limit stated. -Time delay. -Not tested for difficult situations.

2018). Table 8 shows other different control methods applied for PV systems to meet the standards and GCs requirement. It can be noticed that these methods have been achieved the requirements in different degrees; however, there still some limitations which need more concern in future studies. Overall, fulfilling the requirements at the connection point between the RESs and main grid will ensure the injection of high-quality generated power into the power system, improving the system security and stability.

6. Harmonization of the interconnection requirements

The aforementioned comparison of the interconnection requirements concerning the integration of RESs has highlighted how much these regulations differ between countries and power system operators. Therefore, it is difficult to establish a precise technical or financial explanation of the present connection requirements due to the various operational methods of national grids and various integration levels of RPPs worldwide. For example, some countries' GC and standards enforce VRT capability control for every RES linked to the grid regardless of the interconnection level, whereas some countries, such as Germany, only impose VRT requirements for large-scale RESs. This distinction has caused inefficiencies in some regulation controllers and forced additional expenses on the developers and manufacturers of RPPs.

The European Renewable Energy Council (EREC) (Re-thinking 2050, 2015) and European Wind Energy Association (EWEA) (European Wind Energy Association, 2018) require power system operators to improve their advanced and recent interconnection requirements in a consistent and harmonized manner. Harmonized integration regulations will provide maximum efficiency for all the events and ensure that they can be employed wherever appropriate and possible. The RES manufacturers are constantly challenged to modify the hardware and/or software design to ensure that the requirements of each entity are satisfied. Therefore, developing a unique, appropriate, and efficient global design will reduce the cost and make win-win satiation for manufacturers and operators. The main objectives of global harmonization can be summarized as follows:

- to facilitate similar improvement and manufacturing procedures across the globe, reducing the overall cost;
- to set unique and adequate regulations with respect to the incorporation of large- or small-scale RPPs into the grid; and
- to develop efficient technical regulations that depend upon various power system operators' experiences and backgrounds.

The developed requirements should ensure economic efficiency. Expensive technical regulations are required only when needed for ensuring a stable, secure, and reliable power system operation. Additionally, it may be possible to ignore some expensive regulations when RPP penetration is low. There is a minimal requirement for harmonizing the technical integration requirements in areas that have a low impact on the overall cost of the RESs. In other respects, the technical requirements must consider the penetration level, power system robustness, and/or renewable generation technology. Furthermore, the integration requirements of various areas, countries, and organizations may still vary in the future.

7. Conclusion and recommendations

RESs offer methods for generating electricity with minimal environmental impacts. However, because of their high integration levels, various standards, rules, and requirements have been issued for ensuring stable and secure operation of the power system. This review investigated the current trend of renewable power sources around the globe and investigated and compared the various recent requirements and standards with respect to the integration of RESs into the grid for ensuring grid stability. The requirements discussed in this study include VRT, reactive current injection/absorption, voltage and frequency variation, power quality, and active and reactive power regulation. Further, the state-of-the-art compliance technology and control methods proposed to fulfill these requirements are discussed. Moreover, the harmonization of the integration requirements is discussed to present a comprehensive overview and to recommend that the regulations should consider the techno-economic conditions. The review outcome implies that the high integration of RESs into the grid needs more attention, regulation, and standards in which these plants act like conventional power plants. The current integration requirement and standards are varied substantially from one system operator to others and not sufficiently clear, technically and economically justified. This could impose an additional cost on RESs equipment manufacturers and developers. Thereby, global harmonization of these requirements would assist the manufacturers in developing a market-oriented 'universal' RESs equipment. On the other hand, at the renewable energy side, during unbalanced grid conditions, the RES connected to the grid will be affected which needs more investigation. The important issues that may happen are (*a*) overvoltage incident at the RES dc side; (*b*) in grid-connected PV, occurrence of sag and swell can change the rate of reactive power flow in the system, which in turn affects the power factor (*c*) oscillations on the dc-link, power, voltage and current signals which has negative effects on equipment such as power electronic devices; (*d*) unbalanced grid voltages and harmonic distortions may increase the overheating, series and parallel resonance, overcurrent and affect power efficiency; (*e*) loss of synchronization; (*f*) islanding; and (*g*) for grid-connected solar system, the voltage ripple of PV array will increase during disturbances, which cause a reduction of the PV system efficiency.

The suggestions for further improvement of the integration requirements, compliance technologies, and controllers to achieve stable and secure utility grids with a high power quality can be summarized as follows:

- the impact of the large-scale penetration of RPPs on the security, stability, and reliability of the power system should be analyzed from the protection perspective. Further investigations and revision of the current regulations should be conducted to cover all the necessary aspects for the robust and stable integration of RESs;
- coordination and optimization techniques with respect to various integration controls should be investigated for ensuring efficient power system operation;
- recently, the verification of RPPs compliance with the technical requirements has been performed using several control and optimization methods. Further, experimental validation is required because the majority of these methods are restricted to simulation analysis;
- an international taskforce, including researchers, developers, manufacturers, and operators, would be useful to universally harmonize the integration requirements based on penetration expansions and the cost-benefit ratio;
- the international power system operators should aim to adopt a constant numerical value for each integration requirement to minimize the variation between various technical requirements; • only the connection requirements that are strictly needed to ensure the stable and secure operation of the electrical networks should be considered, avoiding expensive regulations, especially in case of small-scale RPPs, and creating a

win-win situation for RPP manufacturers, grid operators, and investors; and

- The comprehensive management and coordination of RES integration remains a relatively unexplored area of investigation and requires more research.

Because the RESs may dominate the power market in the future, these suggestions may contribute to ensuring the maturity of renewable power generation, the improvement and implementation of the penetration requirements. Furthermore, these recommendations may provide a concrete foundation for power system operators, developers of RESs, and manufacturers with respect to the future development of regulations for the connection of RESs to the electrical grid.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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