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Mini review

Challenges of existing grid codes and the call for enhanced standards

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Abstract: The escalating penetration of renewable energy, notably wind and solar, introduces unique complexities into power systems, particularly in frequency and voltage regulation. Current grid codes are inadequate for these emerging dynamics, necessitating significant enhancements to cope with the evolving energy landscape. The paper highlights several pivotal areas of improvement, including increased flexibility within power systems, integration of energy storage systems, expansion of ancillary services, the inclusion of grid-forming inverters, and the international harmonization of grid codes. The research underscores that conventional power system methodologies, primarily reliant on traditional power plants, fail to manage the fluctuating supply-demand dynamics of renewable energy effectively. By proposing improvements in grid codes, the research contributes towards resolving this issue. Furthermore, the paper underlines the paramount importance of international harmonization of grid codes for system interoperability, efficient operation, and exchange of best practices across diverse regions. Through its exhaustive exploration and recommendations, the study empowers policymakers, grid operators, and energy producers to advance grid code frameworks. Consequently, this facilitates renewable energy integration, ensures grid stability, and paves the way for a more sustainable energy future.

Keywords: grid codes; frequency control; voltage control; renewable energy sources; variable renewable energy; power system integration

1. Introduction

Grid codes play an important role in governing the requirements and regulations for connecting generators and loads to the electrical grid. These regulations provide guidelines for reactive power management, fault ride-through capabilities, frequency and voltage control, and power quality. Their adherence is essential for integrating renewable energy sources into the power grid to ensure safe, dependable, and efficient operation. Traditional grid standards, however, were primarily created at a time when renewable energy sources did not constitute a significant portion of the energy portfolio. Renewable energy penetration, technological improvements, and operating procedures have led to numerous revisions in the grid codes. These changes seek to achieve a compromise between maintaining stable development and operation of the power system while providing timely updates to reflect evolving requirements. For example, in Denmark, the initial grid code for wind power plants was introduced in 1999, with significant updates following in 2004, 2010, and 2015 [1,2]. On the other hand, India established their first grid code in 1999, underwent a major revision in 2010, and another revision in 2022 [3].

As renewable energy sources are expected to dominate future power systems, the development of enhanced grid codes specifically tailored to high renewable energy penetration scenarios becomes a critical and timely endeavor. These enhanced grid codes need to address the challenges associated with frequency and voltage regulation in power systems integrated with renewable energy sources. The complex dynamics introduced by renewable energy sources require grid codes that provide clear guidelines and standards for effective frequency and voltage control. The problem at hand is the need for improved grid codes that can effectively manage the complexities of renewable energy integration, ensuring grid stability, maintaining power quality, and enabling the seamless operation of renewable energy sources within the grid framework.

Existing grid codes face several challenges in effectively regulating frequency in power systems. One significant challenge is the integration of high levels of variable renewable energy (VRE) sources, such as wind and solar PV. While the worldwide total renewable capacity was at 3064 GW in 2021, most of the RES expansion is attributed to solar and wind energy new installations [4]. The intermittent nature of VRE generation poses difficulties in maintaining frequency stability, as the power output fluctuates with changing weather conditions. Grid codes of many countries/regions lack specific guidelines for VRE generators to contribute effectively to frequency control, including their participation in frequency response and provision of ancillary services. This results in suboptimal utilization of renewable energy resources and potential frequency deviations. Furthermore, the growing deployment of distributed energy resources (DERs) adds complexity to frequency regulation. DERs introduce additional variability and uncertainties in frequency response, and grid codes need to address their role and requirements for frequency control. Additionally, the limitations of grid-following inverters, which rely on external voltage references and have slower response times, pose challenges to achieving precise frequency regulation. The adoption and standardization of grid-forming inverters, which can operate autonomously and establish grid parameters, require updates and guidelines in grid codes.

Furthermore, there are numerous challenges in reactive power control that have not been adequately addressed by existing grid codes. One such challenge is the lack of harmonization in methodologies and approaches for reactive power control across different grid codes and countries. The absence of standardized guidelines and practices hinders effective management and coordination of reactive power exchange between generators and the grid. This lack of harmonization leads to limitations and gaps in the current grid codes. For instance, there may be variations in the specified thresholds for power factor control or reactive power regulation, creating inconsistencies in the operation and coordination of power systems. These variations can impact the stability and reliability of the electrical grid, especially with the increasing integration of renewable energy sources. The implications of inadequate reactive power control in power systems are significant. Without effective regulation, voltage stability can be compromised, leading to voltage fluctuations or drops that can disrupt the operation of sensitive equipment and impact the quality of power supply. Additionally, an imbalance between reactive power production and consumption can result in increased line losses, reduced system efficiency, and increased costs for grid operators.

This paper addresses the above challenges by exploring the intricacies of frequency and voltage regulation in power systems integrated with renewable energy sources and proposes a roadmap for improving grid codes. By enhancing grid codes, clear guidelines and standards for frequency and voltage control can be established, paving the way for a resilient, sustainable, and renewable energy landscape. In this paper, the term "grid" refers to electrical power systems operating at voltage levels ranging from 110 to 400 kV. Furthermore, this study primarily focuses on transmission-level grids and does not delve into behind-the-meter and distribution level Distributed Energy Resources (DER). Future work could extend the analysis to these areas. The grid codes analyzed in this study are generally applicable to synchronous generators, PV inverters, and wind turbines, but may not cover all types of electrical units.

The subsequent sections will delve into the requirements for frequency and voltage management, low voltage ride-through (LVRT) and high voltage ride-through (HVRT) capabilities, reactive power regulation, and the provision of ancillary services. Additionally, we will highlight the need for flexibility in power systems, the inclusion of energy storage systems, the expansion of ancillary service provisions, the establishment of grid-forming inverter standards, and the importance of international harmonization of grid codes. These areas will be explored to address the challenges posed by the integration of renewable energy sources and to pave the way for more effective grid codes that support the transition towards a sustainable energy future.

2. Grid codes worldwide

Each country has its own set of grid codes that are adapted to the unique characteristics and priorities of its power system. They address various aspects such as frequency response, reactive power control, power factor regulation, LVRT and HVRT. Table 1 lists a few instances of the frequency and voltage control needs in different countries/regions.

Table 1. Technical requirements for frequency and voltage control in power systems with renewable energy sources.

Organization	European Union ENTSO-E	United States Federal Energy Regulatory Commission (FERC)	China National Energy Administration (NEA)	India Central Electricity Regulatory Commission (CERC)
Frequency control	Technical requirements for frequency control in power systems integrated with wind and solar energy sources [5]	Technical requirements for frequency control in hybrid power systems, including primary, secondary, and tertiary frequency control specifications, and guidelines for integrating renewable energy sources	Technical requirements for frequency and voltage control in hybrid power systems [6]	Technical requirements for frequency and voltage control in power systems integrated with wind and solar energy sources [3]
Voltage control	Requirements for voltage control in hybrid power systems outlined in the European Network Code on Requirements for Grid Connection of Generators (NC RfG) [1]	Requirements for reactive power support, power factor control, and compliance regulations for wind and solar energy sources- FERC Order 845 [7]	Requirements for reactive power control, power factor control, voltage stability, and testing and certification requirements for voltage control equipment	Requirements for reactive power control, power factor control, voltage stability, and testing and certification requirements for voltage control equipment

2.1. Frequency control in international grid codes

Frequency control is a crucial element embedded within international grid codes, designed to regulate and monitor deviations in grid frequency. These codes delineate the permissible range within which the power system should operate, while also establishing the responsibilities of power generators in responding to frequency deviations resulting from disturbances. By adhering to these requirements, generators ensure a prompt and effective response to maintain a stable frequency level. The specific allowable frequency deviation range varies among grid codes, with some allowing wider ranges, such as ±1.0 Hz, while others enforce narrower limits, like ±0.5 Hz. These limits are determined by considering factors such as system inertia, generator response capabilities, and the imperative of frequency restoration.

To adhere to the requirements of grid codes, power generators must adjust their active power output in response to frequency deviations. Through the dynamic modification of active power, generators contribute to the stabilization of grid frequency, effectively restoring it to within the acceptable range. In addition to frequency deviation limits, certain grid codes also define thresholds for the rate of change of frequency (RoCoF), denoting the speed at which frequency changes over time. These RoCoF limits ensure that frequency variations occur at manageable rates, preventing abrupt and excessive changes that could jeopardize the stability of the power system. RoCoF limits differ across various grid codes, commonly ranging from 0.5 to 1.0 Hz/s.

The significance of fast frequency services becomes particularly pronounced in countries with substantial integration of renewable energy sources. Countries such as Ireland, United Kingdom, Australia, and New Zealand, as shown in Table 2, face distinctive challenges due to their reliance on variable renewable generation and the subsequent reduction in system inertia. This decline in system inertia exacerbates frequency excursions and increases RoCoF during power imbalances. Since these systems are often isolated from larger power grids, they have limited access to the stabilizing influence of conventional synchronous generators. Consequently, the responsibility for maintaining frequency stability rests on the new technologies that form a substantial portion of their energy mix.

To overcome this challenge, the deployment of fast frequency response devices and services becomes imperative. These services enable swift adjustments in active power output to counteract frequency deviations and uphold system-wide stability. By preventing adverse consequences such as wind farm tripping, customer load shedding, and potential system-wide blackouts, these fast frequency response devices and services assume a crucial role. Advanced control systems, demand response mechanisms, and energy storage technologies form integral components in achieving fast frequency services. These cutting-edge technologies facilitate rapid adjustments in power output, enhance system response time, and provide the indispensable ancillary support necessary for stable grid operation.

Addressing the need for fast frequency services necessitates a comprehensive approach that encompasses revisions to grid codes, technical interventions, and market mechanisms. Grid operators in these countries are actively enhancing their grid codes to accommodate the specific challenges posed by the high penetration of variable renewable sources. They are exploring innovative solutions to enhance frequency response capabilities and ensure the seamless integration of renewable generation into power systems. Through the continuous adaptation and optimization of their grid codes, these countries strive to foster a resilient and sustainable energy landscape.

Table 2. International new fast frequency services.

Country	System services	Type	Response time	Duration	Target
Great Britain (National grid)	Enhanced frequency control capability (EFCC)	Post-fault	0.5 s	N/A	Renewable technologies, demand side resources, and other new technologies
Ireland and Northern Ireland (EirGrid)	Fast frequency response (FFR)	Post-fault	2.0 s	8.0 s	Wind and other emerging technologies
Australia (AEMO)	Fast frequency response (FFR)	Post-fault	1.0 s	N/A	Wind and other technologies
Canada (Hydro-Quebec)	Fast frequency response (FFR)	Post-fault	1.5 s	9.0 s	Wind turbine (6% rated capacity boost)
USA (ERCOT)	Fast frequency response (FFR)	Post-fault	0.5 s	FFR1: up to 10 min FFR2: indefinite (longer than 10 min)	Wind cannot provide response for 10 min Demand response and Battery energy storage

2.2. Reactive power control in grid codes

Reactive power control constitutes another vital element encompassed within grid codes, bearing profound significance in the preservation of voltage stability and the regulation of power factor. These codes establish precise guidelines governing the exchange of reactive power between generators and the grid, ensuring the efficient and reliable operation of the electrical system. Although these requirements may exhibit variability among countries, their overarching objective is to uphold voltage within specified limits and achieve the desired power factor, whether leading or lagging, as dictated by the grid's particular exigencies. Reactive power control is typically implemented through a range of control strategies and equipment, including voltage control, voltage-reactive power droop control, and power factor control. These strategic approaches empower generators to modulate their output of reactive power in response to the voltage and power factor requisites set forth by the grid. Certain grid codes mandate power factor control, guaranteeing that generators uphold a designated power factor within predetermined thresholds. This control mechanism assumes a pivotal role in governing the flow of reactive power and stabilizing voltage levels. Moreover, grid codes may specify an acceptable range of power factor values, thereby allowing for flexibility in adjusting the power factor in alignment with prevailing system conditions.

Voltage control stands as another pivotal facet of reactive power control. Grid codes typically necessitate the active participation of generators in voltage regulation by adjusting their reactive power output to maintain voltage within a predefined range. By actively managing reactive power, generators contribute to the stability of grid voltage, compensating for voltage fluctuations or drops that may arise due to system contingencies or variations in load demand. Reactive power control proves to be of utmost importance for grid stability, particularly with the growing penetration of renewable energy sources. As renewable technologies, like wind and solar, become integral to the grid, their variable and intermittent nature can exert an impact on voltage and power factor. The provisions for reactive power control in grid codes ensure that renewable generators actively take part in upholding voltage stability and power factor regulation, thus facilitating their seamless integration into the grid.

It is worth noting that specific requirements and methodologies for reactive power control differ among grid codes and countries. Each grid code is meticulously tailored to the unique characteristics and requirements of the electrical system it governs. For instance, in the European Union, the European Network Code on Requirements for Grid Connection of Generators (NC RfG) outlines the requirements for voltage control in hybrid power systems. Similarly, in the United States, the Federal Energy Regulatory Commission (FERC) mandates reactive power support, power factor control, and compliance regulations for wind and solar energy sources through FERC Order 845.

2.3. Low voltage ride-through (LVRT) and high voltage ride-through (HVRT) requirements

The requirements for low voltage ride-through (LVRT) and high voltage ride-through (HVRT) in international grid codes hold an enormous importance in safeguarding the stability and dependability of power systems during voltage disturbances. These requirements impose specific capabilities on renewable energy generators, particularly wind turbines, to withstand and ride through fluctuations in voltage.

LVRT focuses on the ability of renewable generators to remain connected to the grid and continue operating even when confronted with low voltage conditions arising from faults or disturbances. Grid codes outline precise voltage levels, durations, and response expectations for generators during such events. It's worth noting that these requirements may differ from one country to another, reflecting the distinct grid characteristics and system demands across regions. For instance, in Germany, wind turbines are mandated to endure voltage dips down to 0.85 per unit (p.u.) for a defined duration, while in Denmark, the LVRT requirement sets the voltage dip limit at 0.9 p.u. within a specific period. Similarly, grid codes in the United States, Australia, and other countries delineate the acceptable voltage dip levels and ride-through times that wind turbines must adhere to during fault events. Figure 1 depicts the LVRT curves of different European countries [8].

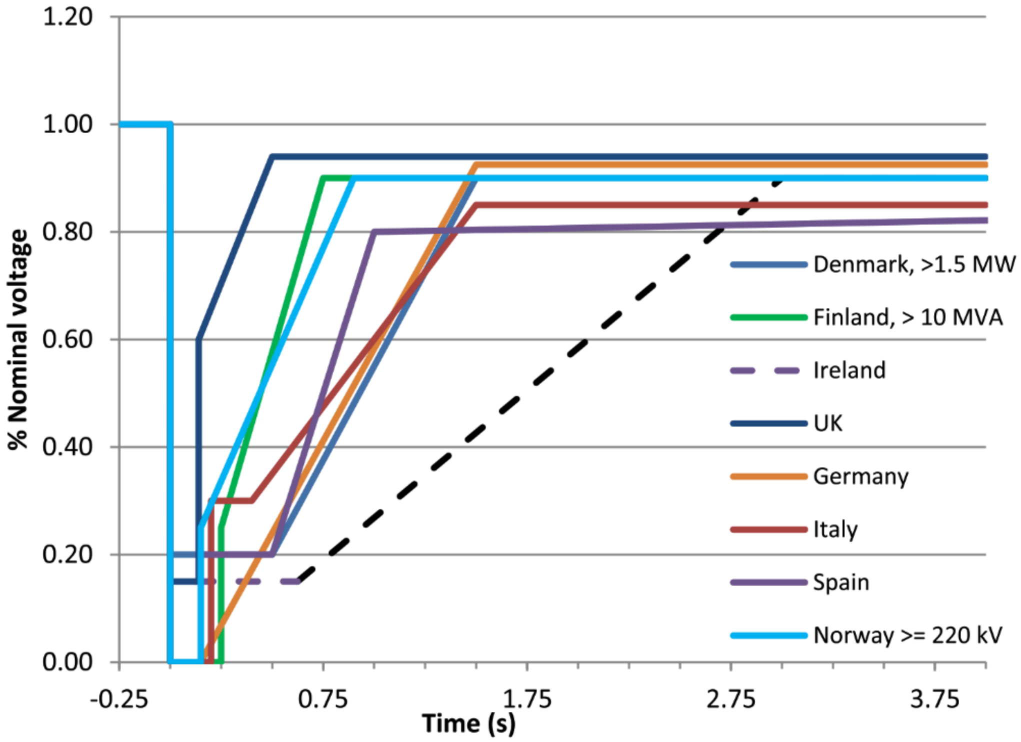

Figure 1. LVRT curves for different European countries.

Conversely, HVRT pertains to the capability of renewable generators to withstand high voltage levels without tripping or disconnecting from the grid. This becomes crucial when encountering voltage surges or other instances of elevated voltage conditions. Grid codes establish the maximum voltage levels and durations that generators must withstand to ensure seamless operation. For example, in Spain, wind farms are required to endure voltage surges up to 1.3 p.u. for a specified duration, while in the United Kingdom, wind turbines must sustain voltage levels up to 1.1 p.u. within a certain period, as illustrated in Table 3 [9]. These requirements are designed to guarantee that generators remain connected and continue operating even amidst transient instances of high voltage events.

In addition to the LVRT and HVRT requirements, some grid codes also specify the need for reactive current or power support functions. These functions are designed to enhance grid voltage stability during fault conditions. Reactive current support is particularly crucial during transient voltage dips or surges, as it aids in maintaining the voltage profile of the grid. This is often achieved through advanced control algorithms that dynamically adjust the reactive power output of generators. For instance, during a voltage dip, the generator can inject reactive power into the grid to support the voltage levels, thereby aiding in quicker recovery and stabilization. Comparatively, the reactive power control mechanisms described in Section 2.2 primarily focus on steady-state operations and are not specifically tailored for transient fault conditions. While these control mechanisms are essential for maintaining long-term grid stability, the reactive current support functions in LVRT and HVRT controls offer a more dynamic response, which is critical during short-term disturbances.

By enforcing LVRT and HVRT requirements, grid codes aim to ensure the stable operation of power systems, uphold grid reliability, and facilitate the seamless integration of renewable energy generation. These requirements establish a framework for renewable generators to actively contribute to grid stability and support the overall resilience of power systems.

Table 3. HVRT requirements in various grid codes.

	HVRT		Power factor	
	Vmax (p.u.)	Tmax (s)	Leading	Lagging
Australia	1.3	0.05	0.93	0.93
Denmark (for more than 1.5 MW)	1.2	0.1	0.975	0.975
Tennet onshore	1.26	0.1	0.95	0.925
India	-	-	0.95	0.95
Ireland	1.1	-	0.95	0.95
Spain	1.3	0.5	0.99	0.99
UK	1.1	-	0.95	0.95
China	-	-	0.95	0.95
USA ERCOT	1.175	0.2	0.95	0.95

2.4. Fault ride-through capabilities and system transient stability

System transient stability refers to the ability of a power system to maintain synchronism following a large disturbance, such as a fault or a sudden change in load. The critical fault clearing time is an essential parameter in this context. It is the maximum time within which a fault must be cleared to ensure that the system remains stable. Studies have shown that grid-forming converters can significantly influence this critical fault clearing time. For example, when transient stability improvement measures are implemented in grid-following converters, the Remote Irish electrical network can function reliably with less than 30% grid-forming contribution, even under conditions of a three-phase fault. This is an improvement over the 40% requirement without these controls. Additionally, any oscillations that occur during and after the fault are rapidly stabilized [10]. This is primarily because grid-forming converters can provide fast and robust voltage and frequency support, thereby enhancing the system's ability to withstand transient disturbances. Moreover, the synchronization stability of grid-forming converters is closely related to the system's transient stability. These converters can autonomously establish grid parameters like frequency and voltage, making them pivotal in maintaining system stability during faults. Their ability to quickly synchronize with the grid post-fault enhances the overall resilience and reliability of the power system.

Therefore, it is imperative for grid codes to include specific requirements concerning the FRT capabilities of grid-forming converters. These should be aimed at optimizing their performance to improve system transient stability, thereby ensuring a more resilient power system.

However, there are certain aspects that could be considered for inclusion in existing codes to further enhance the ride-through capabilities.

These aspects include:

Response time: The response time of renewable generators during voltage disturbances is a crucial factor in maintaining grid stability. Existing codes could specify the maximum allowable response time for generators to recover and return to normal operation following a voltage dip or surge.

Voltage sag/swell characteristics: In addition to voltage dip and surge levels, it may be beneficial to include specifications related to the duration and characteristics of voltage sags and swells. This would provide more comprehensive guidelines for renewable generators to ride through varying voltage conditions.

Fault clearance requirements: Existing codes primarily focus on the behavior of renewable generators during voltage disturbances. However, incorporating fault clearance requirements can further enhance the ride-through capabilities. This would involve specifying the actions and response of generators during fault events, ensuring their safe and efficient reconnection to the grid after the fault is cleared.

Advanced control strategies: The inclusion of advanced control strategies and technologies in grid codes can enhance the ride-through capabilities of renewable generators. These strategies may include the use of advanced control algorithms, fault detection and isolation mechanisms, and coordinated control schemes to improve the dynamic response of generators during voltage disturbances.

Harmonization of requirements: Harmonizing the LVRT and HVRT requirements across different grid codes and countries can provide consistency and interoperability. It would facilitate the integration of renewable energy generation across regional and international power systems, ensuring seamless operation and improved grid resilience.

Incorporating these aspects into existing grid codes would further strengthen the ride-through capabilities of renewable generators and enhance their contribution to grid stability and reliability. By continuously updating and refining the codes, power system authorities can ensure the effective integration of renewable energy sources and promote the sustainable development of power systems.

3. Limitations of current grid codes and the need for enhanced codes

Historically, grid codes were primarily designed with a focus on synchronous generators and conventional power plants, assuming their predominant presence in the energy landscape. The rapid growth of VRE generators in the grid prompted power system authorities, in collaboration with operators and other stakeholders, to develop and implement updates and revisions in grid codes. These changes aim to establish a common operational framework that enables efficient interactions and functioning among system operators, suppliers, and consumers, while maintaining individual responsibilities within their respective scopes [1]. While a few countries are very proactive with respect to revisions of their grid codes, many countries have outdated grid codes with numerous limitations. To address the limitations of current grid codes and enhance their effectiveness in facilitating the integration of renewable energy sources, various key areas, described below need consideration.

3.1. Insufficient flexibility

Flexibility can be defined as the capability of the electric power system to respond to fluctuations and uncertainty in supply and demand in order to restore stable and safe electricity system operation [11]. Conventional flexibility resources encompass a range of options, including flexible consumption and generation resources, electricity storage, and grid interconnection [12]. Traditionally, the need for flexibility was met by rapidly adjusting output in conventional power plants, which could switch between full load and minimum stable generation. These plants carefully considered cost structures, technical operations, and opportunity costs when participating in different segments of the electricity market. However, in a fully decarbonized electricity system, the absence of conventional power plants poses a challenge to meeting the corresponding flexibility requirements. Therefore, the ability to harness decentralized flexibility sources becomes strategically important for the future electricity system, given that globally, the share of wind and solar in power generation rose to over 12% in 2022 [13]. Additionally, addressing the demands of distribution grid management calls for diversifying the sources of flexibility.

To enhance flexibility, grid codes could incorporate advanced control algorithms and demand-side management techniques. These would allow for real-time adjustments to grid operations, accommodating the variable nature of renewable energy sources. In Europe, ongoing efforts are already underway to develop a network code focused on demand side flexibility. This code aims to provide a clearer understanding of the concept of demand side flexibility and establish well-defined roles and responsibilities for all stakeholders involved [14]. Currently there are barriers hindering the scaling up of demand side flexibility. To effectively overcome these barriers, SmartEN, Europe’s association for smart energy, emphasizes the need for the network code to enhance transparency regarding the grid’s requirements, facilitate interactions between market participants, and adopt a market-oriented approach to flexibility procurement [15]. In addition to this, it is proposed that the network code should offer cost-efficient solutions for integrating renewable energy sources and promote the expansion of electrification as a viable alternative to grid reinforcement.

3.2. Requirements for energy storage systems

Due to the increasing decentralization of the power system, with the integration of battery storage, solar PV, and micro-CHP generators, the distinction between power generators and consumers is becoming less clear. As a result, it is becoming necessary to establish technical requirements in grid codes for these combined consumer-producer connections. Currently, the European grid connection network codes do not include specific requirements for energy storage systems. This is a significant gap, given that the European energy storage market is expected to reach more than 200 GW by 2030 and 600 GW by 2050 [16] (from roughly 60 GW in 2022, mainly in the form of pumped hydro storage). However, the Grid Connection European Stakeholder Committee acknowledges the need to treat an electricity storage module the same way as a power generating module. Therefore, an electricity storage module is expected to meet the same requirements as a power generating module, both in generating mode and consumption mode, with additional requirements as necessary [17]. Different member states have adopted various approaches to address energy storage in their grid codes, as depicted in Table 4.

Table 4. Approaches to address energy storage in grid codes.

Member state	Approach to address energy storage in grid codes
Belgium	Groups storage with power park module technology.
	Specific grid code section for storage (except pumped hydro).
	Covers frequency control, robustness, voltage stability, reactive power capacity, etc. [18].
Finland	Develops own specifications for storage, aligned with European grid connection network codes.
	Includes requirements for controllability, operating frequency and voltage ranges, fault behaviour, protection, etc. [19].
Great Britain	Considers energy storage as a subset of power generation modules.
	Applies minimum requirements for generators to energy storage systems.
	Specifies conditions for controllability and functionalities [20].
Germany	Distinguishes among facilities for EV charging, storage, consumption, and generation.
	Includes separate technical connection requirements among facilities but applies generator conditions to all active power injections.
	Active power conditions apply when injecting power into the system [21].

The current grid codes lack explicit requirements and guidelines for energy storage systems, leading to uncertainties and challenges in their connection and operation. Therefore, the development of grid codes tailored to energy storage systems is essential to provide clarity, promote interoperability, and enable the full utilization of their capabilities in supporting grid stability, flexibility, and the integration of renewable energy sources.

3.3. Limited provision for ancillary services

The provision of ancillary services is vital for maintaining grid stability and reliability in the power system. While some ancillary services are already included in grid codes, there is a need for further development of codes to address the evolving requirements and challenges associated with these services [22]. Grid codes should be updated to include a broader array of ancillary services, such as frequency restoration reserves and ramping products, to ensure effective grid flexibility and system reliability.

The increasing integration of variable renewable energy sources, such as wind and solar PV, along with the emergence of new technologies like energy storage, necessitates a comprehensive framework for ancillary service provision. One key aspect that requires attention is the remuneration and market participation of ancillary services [23]. The economic viability of flexibility provider projects, including energy storage, heavily relies on the availability of remunerated ancillary services. Therefore, it is crucial to establish clear guidelines and mechanisms within grid codes to ensure fair compensation for the provision of ancillary services. This will encourage the deployment of flexible resources and promote the efficient utilization of renewable energy assets.

Furthermore, as the power system becomes more decentralized and dynamic, there is a need to expand the range of ancillary services addressed in grid codes. While some services like reactive power provision and primary reserve are commonly included, other services such as frequency restoration reserve, ramping products, and additional inertial response are not be explicitly specified [1]. Developing codes that encompass a broader set of ancillary services will enhance grid flexibility, enable the integration of emerging technologies, and ensure system reliability during both normal and emergency operating conditions. The evolving nature of variable renewable energy sources also requires the inclusion of specific provisions in grid codes. Due to the distinctive dispatching rules and variable cost assignment of VRE generators, such as wind and solar PV systems, grid codes must consider their unique attributes. This entails the formulation of explicit directives for VRE generators to actively participate in ancillary services like frequency control, reactive power capability, and voltage regulation. By incorporating these specifications into grid codes, the maximum benefits of VRE generation can be realized, ensuring the preservation of grid stability and the provision of high-quality power supply.

3.4. Grid-forming inverter standards

A grid-forming inverter refers to a power electronic device endowed with the ability to independently establish grid parameters, such as frequency and voltage, without relying on an external voltage reference. In contrast to grid-following inverters, which necessitate an external voltage source for frequency reference, grid-forming inverters can function autonomously as self-sustained units, playing a pivotal role in the transition of power systems towards the integration of renewable energy. While grid-following inverters currently dominate grid configurations, the adoption of grid-forming inverters is garnering attention due to the escalating penetration of renewable energy sources and the imperative for grid stability. Nonetheless, challenges persist, including the absence of established standards and a clear understanding of the requirements and functionalities associated with grid-forming inverters. The definition and scope of grid forming remain subjects of active research, lacking consensus within the field. Additionally, the existing grid codes predominantly emphasize grid-following inverters, reliant on external voltage references and unable to operate autonomously. These grid-following inverters, also known as grid-supporting or grid-feeding inverters, require voltage angle and frequency measurements using a phase-locked loop, resulting in non-instantaneous response times. To overcome these limitations, the development of grid codes that precisely define and specify the technical requisites and functionalities of grid-forming inverters is imperative. This entails the establishment of standards and guidelines for grid-forming capabilities, accompanied by the mandatory inclusion of such requirements in grid-connected facilities. Grid codes should define and specify the technical requirements for grid-forming inverters, including their roles in maintaining grid stability and facilitating the integration of renewable energy sources.

3.5. Harmonisation of grid codes

The international harmonization of grid codes holds huge importance in facilitating the seamless and optimal functioning of power systems across diverse countries and regions. Although achieving harmonization may entail substantial time and effort, the advantages it brings far outweigh the challenges faced. Harmonized grid codes establish consistent technical requirements and standards, ensuring interoperability and effective collaboration among a wide array of stakeholders [24]. A pivotal rationale for pursuing grid code harmonization lies in addressing the distinct needs of small countries or power systems with limited market influence. Through the establishment of harmonized requirements, these smaller systems can access functionalities pertaining to frequency and active power control, even in the absence of individual capabilities to enforce such requirements autonomously. Harmonization empowers the implementation of cost-effective solutions specifically tailored to the unique characteristics of these systems, thereby facilitating their integration into larger regional grids.

In larger interconnected systems, harmonization of grid code requirements related to frequency and active power control is essential for ensuring the overall stability and security of the entire synchronous system [25]. By aligning these requirements across the region, operators can enhance system predictability and response during frequency disturbances. Harmonized grid codes promote the effective sharing of flexibility resources, enabling smoother energy transitions and supporting the integration of renewable energy sources. Furthermore, harmonization of grid codes can lead to economies of scale and cost savings. When requirements are harmonized, equipment manufacturers and project developers can design and produce standardized solutions that comply with the regional grid code specifications. This reduces the need for customizations and lowers development and implementation costs. By streamlining processes and facilitating compatibility, harmonization fosters a more competitive market environment and promotes the widespread adoption of efficient technologies and practices.

The exchange of experiences and lessons learned through international co-ordination is another compelling reason for harmonizing grid codes. By sharing best practices and avoiding the repetition of mistakes, operators can collectively improve the reliability, performance, and resilience of power systems. Harmonization allows for the collective advancement of grid code frameworks, benefiting all participants by fostering innovation, operational efficiency, and increased grid reliability. A global initiative could be undertaken to standardize grid codes, ensuring interoperability and effective collaboration among different countries and regions.

4. Conclusions

This study sheds light on the complexities and challenges posed by existing grid codes in the context of power systems integrated with wind and solar energy sources. While renewable energy integration offers opportunities for a sustainable future, it also presents intricate issues regarding frequency and voltage regulation that require resolution. By examining the limitations of current grid codes and proposing enhancements, this research contributes to the ongoing efforts to effectively integrate renewable energy sources into power systems.

The findings underscore the necessity for enhanced grid codes capable of accommodating the increasing penetration of renewable energy sources. One crucial aspect that demands attention is the need for flexibility within the power system. Conventional approaches relying on traditional power plants prove inadequate in managing the supply and demand fluctuations introduced by renewable energy sources. To overcome this challenge, it is crucial to develop grid codes that embrace demand-side flexibility and incorporate cost-efficient solutions for the seamless integration of renewable energy sources. Furthermore, incorporating technical requirements for energy storage systems within grid codes is imperative. Energy storage plays a vital role in mitigating the intermittent nature of renewable energy generation, bolstering grid stability, and optimizing the utilization of renewable energy assets. By establishing clear guidelines and mechanisms for the integration of energy storage, grid codes can facilitate the widespread deployment and optimal operation of energy storage systems in power systems. The provision of ancillary services represents another critical aspect addressed in this study. Ancillary services are indispensable for ensuring grid stability and reliability, particularly as renewable energy sources become more prevalent. Grid codes should encompass a broader array of ancillary services, including frequency restoration reserve and ramping products, to ensure effective grid flexibility and system reliability under diverse operating conditions. Grid-forming inverters have emerged as promising technologies for power system integration. However, the absence of established standards and requirements for grid-forming capabilities hampers their wide-scale adoption. To fully harness their potential, grid codes must include explicit mandates for grid-forming functionalities, delineating guidelines for their technical requirements and mandating their inclusion in grid-connected facilities. Lastly, international harmonization of grid codes is paramount for the efficient operation and interoperability of power systems across different countries and regions. Harmonized grid codes establish consistent technical requirements and standards, fostering the sharing of flexibility resources, realizing economies of scale, and facilitating the exchange of best practices. Through international collaboration and knowledge sharing, harmonization enhances grid reliability, resilience, and innovation.

As the energy landscape evolves, continuous research and collaborative efforts are essential to refine and optimize grid codes. Policymakers, grid operators, energy producers, and other stakeholders must collaborate to advance grid code frameworks that facilitate the integration of renewable energy sources, ensure grid stability, and foster the transition toward a sustainable energy system. Through these collective endeavors, we can forge a resilient and environmentally conscious future for our power systems.

Use of AI tools declaration

The authors declare they have not used artificial intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest in this paper.

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