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Article

A Comprehensive Comparative Analysis of Grid Code Requirements for Renewable Power Plants and Energy Storage Systems Integration: Technical Requirements, Compliance Assessments, and Future Directions for Türkiye

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Abstract

The rapid integration of inverter-based renewable energy sources (RES), particularly solar photovoltaic (PV) and wind power plants (WPPs), together with the large-scale deployment of battery energy storage systems (BESSs) is fundamentally reshaping modern power systems. While these technologies are essential for decarbonization, their converter-dominated and variable characteristics introduce new challenges for grid stability, operational security, and regulatory compliance. As a result, grid codes are being continuously revised to define advanced technical requirements, including fault ride-through (FRT) capability, reactive power support, frequency response, voltage control, and active power management for RESs and energy storage systems (ESS). This study presents a systematic comparative assessment of international grid codes, examining the technical and operational requirements imposed on inverter-based resources (IBR) and ESSs across multiple jurisdictions. In parallel, the current Turkish Grid Code is evaluated from a future-oriented perspective, and recommendations that can improve the existing regulatory framework are proposed, particularly regarding high-voltage ride-through capability, synthetic inertia provision, fast frequency response (FFR), hybrid power plant (HPP) coordination, and ESS-specific performance criteria. Based on the comparative analysis, the study proposes targeted amendments to the Turkish Grid Code aimed at enhancing system resilience under high renewable penetration levels. Furthermore, field-testing methodologies, model-based validation practices, and emerging digitalized compliance monitoring architectures are investigated to assess their applicability to next-generation power systems. By integrating international best practices with country-specific recommendations, this work contributes to the development of transparent, adaptive, and technically robust grid code compliance frameworks, supporting both academic research and practical grid modernization efforts.

Keywords: active and reactive power control; energy storage system; fault ride through; frequency response; grid codes; renewable power plant; Turkish grid code

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1. Introduction

The rapid proliferation of renewable energy power plants over the past decade has significantly transformed the global electricity generation structure [1]. At the same time, advancements in photovoltaic (PV) and wind energy technologies have facilitated the integration of battery energy storage systems (BESS), leading to increasingly inverter-dominated power systems [2]. By 2024, the share of low-carbon energy sources (renewable and nuclear) in global electricity generation is expected to exceed 40%, with renewable generation reaching a record level of 858 TWh, clearly demonstrating the pace of transformation [3]. This trend indicates that dependence on fossil fuels will gradually decrease and renewable sources will become more dominant in global energy systems [4]. As illustrated in Figure 1, projections for the period 2020–2053 indicate that renewable energy generation and energy storage capacity will grow in parallel, highlighting the increasing role of storage systems in supporting variable renewable energy integration [5].

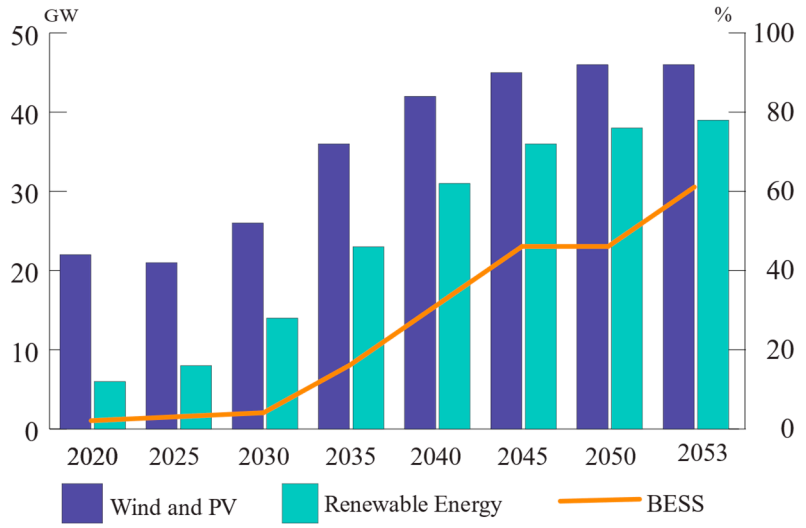

Figure 1. Renewable energy sources (RESs) share and ESS capacity development [5].

Renewable sources such as wind and solar are inherently intermittent and unpredictable [6]. Mismatches between generation and demand result in inefficiencies in existing grids, reducing energy quality and supply reliability [7,8]. Consequently, frequency deviations, voltage fluctuations, and sudden power changes occur more frequently, particularly in regions with high penetration of intermittent generation [9]. The literature emphasizes that these problems significantly complicate grid operation and that traditional control mechanisms cannot always respond adequately to such rapid changes [10,11]. These challenges have positioned ESSs as key enablers in terms of maintaining operational flexibility and stability in renewable-dominated power systems [12]. ESS technologies are among the fundamental solutions for balancing fluctuations in renewable energy generation and improving grid flexibility [13]. These systems play a critical role in ensuring supply-demand balance, supporting frequency and voltage stability, and strengthening overall energy supply security [14]. In particular, ESSs are widely used to manage demand peaks, mitigate sudden generation changes, and enhance grid stability due to their fast response capabilities [14,15]. In this way, ESS enables the safe, stable, and efficient integration of RES into the grid at higher rates [16].

As renewable power plants (RPPs) and ESSs are increasingly deployed to mitigate the operational challenges caused by intermittent generation, both systems have become integral components of modern power systems [17]. Since RPPs and BESSs are predominantly connected to the grid through power electronic interfaces, their dynamic behavior

directly affects grid stability, power quality (PQ), and overall system security [18]. Consequently, ensuring compliance with grid codes, standards, and regulations has become a mandatory requirement for both RPPs and ESSs, regardless of their installed capacity or specific application [19]. Grid code compliance ensures that these systems operate within defined technical limits under normal operating conditions and respond appropriately to grid disturbances such as frequency deviations, voltage fluctuations, and sudden power changes [20,21]. Therefore, systematic verification and documentation of grid code compliance are essential for the safe, stable, and large-scale integration of renewable generation and ESSs into electrical grids [22].

Grid codes are regulatory frameworks that primarily define the technical and operational requirements for generation units connected to electricity grids [23]. In most developed countries, these codes are published by transmission system operators and are continuously updated to ensure system reliability [24]. The literature emphasizes that the integration of variable RESs into weak and isolated grids creates new technical and economic challenges, which directly influence the evolution of grid codes [25]. Comparative analyses of grid codes in countries such as Denmark, the UK, Germany, Spain, the USA, and Canada reveal that the system support capabilities expected from renewable generation facilities are increasingly approaching those of conventional power plants [26].

In particular, requirements such as FRT, reactive power support, and frequency response have become fundamental components of modern grid codes [27,28]. However, ensuring these requirements for IBR has introduced additional engineering challenges, especially due to their interaction with protection systems, where behaviors such as phase selection errors during reactive current injection have been reported [29]. Therefore, grid code compliance must be addressed not only during the design phase, but also through field tests, validated model simulations, and certification processes [30,31]. Country-based case studies conducted under different grid structures, including Indonesia [32,33], Ethiopia [34], Egypt [35], and Türkiye, show that the operational characteristics and integration requirements of variable renewable energy (VRE) systems strongly depend on local grid conditions. In parallel, comprehensive reviews on large-scale PV integration emphasize that the increasing penetration of inverter-based generation introduces new stability and dynamic performance challenges, which require continuous refinement and extension of existing grid code provisions [36]. Moreover, connection requirements for PV and wind power plants (WPP) have expanded to include PQ, island operation, active-reactive power control, and SCADA-based monitoring, while differences between international standards have increased the importance of selecting appropriate standards, particularly in developing countries [37–39].

With the increasing penetration of RPPs, the FRT and dynamic voltage support requirements defined in grid codes have led to more complex control and protection challenges for inverter-based generation facilities [40]. The literature shows that during the implementation of these requirements, inverter-induced fault currents can cause phase selection errors in protection relays, primarily due to their behavior differing from that of traditional synchronous generators [41]. To address this issue, advanced control structures that simultaneously regulate positive and negative-sequence currents have been proposed, demonstrating that reactive current injection requirements and proper protection operation can be achieved simultaneously [41,42]. However, the risk that such current injections may exceed converter current limits has made current-limiting strategies an integral part of grid code compliance [42]. These findings highlight the necessity for grid codes to explicitly define not only static operating limits but also dynamic behavior under fault conditions.

The applicability of grid code requirements is evaluated not only through theoretical definitions but also through case studies, simulations, and validation processes conducted

on actual systems. Ensuring grid code compliance of renewable generation and ESSs requires systematic monitoring, testing, and simulation-based verification approaches [43]. Model validation plays a critical role in confirming the correct performance of control systems and the accuracy of simulation models used for stability and compliance assessments, while practical testing of reactive power capability, excitation systems, and governors is also widely addressed in the literature [44]. In parallel, grid codes increasingly emphasize the consistency between simulation models and the physical behavior of grid-connected assets, highlighting the need for validated and representative models [45]. Compliance verification can be supported through both off-line and on-line methodologies, including disturbance monitoring techniques that compare simulated responses with measurements recorded during real grid events [46]. In addition to simulation-based approaches, on-site testing remains essential, with commercial and standardized test solutions enabling functions such as Low-Voltage Ride-Through (LVRT), High-Voltage Ride-Through (HVRT), and phase angle jump testing under controlled conditions [47,48]. Nevertheless, existing verification and certification practices still face challenges due to the limited specification of simulation procedures and hardware-dependent effects, particularly for reactive power capability assessments, reinforcing the importance of integrated monitoring, testing, and simulation frameworks for reliable grid code compliance verification [30,49,50].

In line with the increasing complexity of grid code requirements and the diversification of grid-connected generation technologies, a broad range of studies have investigated grid code compliance from different system, control, and verification perspectives. As summarized in Table 1, the literature covers a wide spectrum of inverter-based generation assets, including WPPs, PV power plants, ESSs, and hybrid sites, examined at both unit and plant levels. These studies address key grid code requirements such as active and reactive power control, frequency response, fault ride-through (FRT) capability, PQ limits, ramp-rate constraints, and dynamic performance under normal and disturbed operating conditions. In addition to control-oriented solutions, significant attention has been given to compliance verification methodologies, including model validation, real-time simulation, monitoring-based assessment, and certification-oriented testing frameworks. Overall, Table 1 provides a structured overview of representative studies, highlighting the diversity of technical approaches and validation strategies proposed to support grid code-compliant operation of RPPs and ESSs across different grid conditions and regulatory environments.

Table 1. Overview of grid code compliance studies for RPP and ESS.

Ref No.	System/Technology Under Review	Key Technologies	Country Mentioned in the Study
[51]	WPP (50–300 MW), PMSG, DFIG, Fixed-Speed WT	PQ, Grid Impact, Grid Code Compliance	Türkiye
[52]	DG, HV & MV connected generation facilities	Active Power Control, Reactive Power, PQ, Fault Behavior, Protection	Germany, France, UK, Poland, Türkiye
[53]	Wind Farm (WF) (50 MW), DFIG, Full Converter Asynchronous Generator	Load Flow, Short-Circuit, Contingency, Stability	Oman
[54]	Large-Scale Wind Power Plant (LSWPP), Interconnected Power System	RES Grid Codes	NA
[26]	WPP (especially Offshore WPP)	Reactive Power, Frequency Regulation, FRT, PQ, Communication, Ramp Rate	Denmark, Ireland, UK, Germany, Spain, China, USA, Canada
[55]	WPP (WT control methods)	Active Power Reserves, Primary Frequency Control, Synthetic Inertia	ENTSO-E, Spain, Germany, UK, Ireland

Table 1. *Cont.*

Ref No.	System/Technology Under Review	Key Technologies	Country Mentioned in the Study
[31]	Wind Turbine & WPP Dynamic Models	Model Validation, Certification, Commissioning Requirements	Spain, Germany, South Africa
[56]	PV Power Plant (500 MW), IBRs, Synchronous Condenser (160 Mvar)	Reactive Power Capability, FRT, Short-Circuit Current Contribution	Spain
[57]	WF, Wind Turbine Generators (WTGs), Set-point Control Strategy	Power Fluctuation Limitation, Grid-Code Operational Constraints	NA
[58]	Offshore WPP, Wind Turbines, PWM Modulation, Selective Harmonic Elimination	PQ, Harmonic Emission Limits	Germany
[59]	Real PV Power Plant, Simulation Model	Power-Frequency Requirements, Reactive Power Control and Capability	Spain
[60]	WPP (especially Grid-Forming WPPs), Wind Energy Conversion Systems (WECSs) Topologies & Control Strategies	PQ Standards, Dynamic Performance Requirements	Denmark, UK, Australia, Germany, USA
[61]	WPP (Grid-Connected WP), Wind Turbines	PQ, Grid Integration Requirements, AS	Türkiye
[62]	WPP, Measurement & Monitoring Methods, Time-Frequency Analysis	LVRT, Power Factor Requirements, SCADA Compliance	USA
[63]	Type III Wind Turbine (2 MW), Virtual Synchronous Machine Control	GFM Capability Requirements, Virtual Inertia Specifications	UK
[64]	Wave Energy Generation Plant, ESS (Supercapacitor-based ESS)	Active Power Ramp-Rate Limit Compliance	Spain
[65]	WF (9 MW), STATCOM, PI Controllers, Ant Colony and PSO	LVRT	NA
[66]	Offshore WPP, Wind Turbines, GFM Control, HVDC Transmission	Grid Requirements (ENTSO-E framework), AS, Harmonics, Stability Analysis	NA
[67]	Offshore WF (1.2 GW), BESS (400 MW), Electrolyser Plant (400 MW), Hybrid Site (400 kV PCC)	Reactive Power Requirements, FRT, Dynamic Performance Constraints	NA
[68]	Wind Power Projects, HV Grid Connection, Direct Connection, LILO (Loop-In Loop-Out), Substations	HV Grid Connection Requirements, Reliability, System Stability, Grid Code Compliance	NA
[69]	Large-Scale PV Power Plants, Equivalent POI Modeling, Load Flow Validation	AS Requirements, Transmission System Operator Compliance Verification	NA
[70,71]	SPP (Category B SPP), Inverter Model, DIgSILENT PowerFactory Network Model	Reactive Power and Voltage Capability Requirements, PQ	South Africa
[72]	SPP, Smart Inverters, Medium Voltage Distribution Network	Voltage Regulation, Reactive Power Control, Power Factor Limits	NA
[73]	SPP, Operational Forecasting Methods	Forecast Submission Requirements, Penalty Schemes, Grid Integration Standards	NA
[74]	SPP, Distribution Grid Codes	Voltage & Frequency Deviations, Active & Reactive Power Control, Power Factor Control, FRT	Egypt
[75]	ESS Plant (50 MW), Aggregated WECC Model, DIgSILENT PowerFactory	Grid Code Compliance Studies, Requirements for Generators (RfG) Performance Requirements, Aggregated Modeling	UK

Table 1. *Cont.*

Ref No.	System/Technology Under Review	Key Technologies	Country Mentioned in the Study
[76]	Commercial-Scale Power Plants, PCC Voltage Constraints	Grid Code Applicability Assessment, Active Power Control Compliance	France
[34]	RESs, Small & Microgrids	Grid Integration Requirements, Grid Code Normalization, Compliance Testing	Ethiopia
[77]	Residential Grid-tied and Off-grid (PV, WPP, ESS)	Techno-Economic Analysis & Optimization	Türkiye
[78]	Offshore WF High-Voltage Direct Current (MMC-HVDC connected)	AC Voltage & Frequency Control, Fault Current Injection	NA
[79]	Large-Scale WPP (Grid-Connected & Islanded)	WPP Modeling, SCIG-based WTGU, Grid Code Compliance (RTDS/RSCAD)	South Africa
[80]	HPPs, Wind Farms, MPPC) (PSS/E, PSCAD)	Interconnection Requirements, Advanced Grid Functions, Dynamic Performance Compliance	USA, Australia
[81]	PV Systems, IEC PV Standards	Quality Certification, Safety Standards, PV Technical Standards	India
[82]	Grid-Connected PV Systems, Inverter Control, Data-Driven Curve Fitting Model	Reactive Power Management, Voltage Stability, Grid Compatibility	NA
[39]	Utility-Scale PV Power Plants, IBRs	Grid-Connection Requirements (Normal & Abnormal Conditions), IEEE 1547 Compliance	Germany, UK, Australia, Denmark, Egypt, Malaysia
[83]	RPP, Wind Farm Model, Real-Time Simulation Testbed	Voltage Requirements, Frequency Requirements, Short-Circuit Response, Reactive Power Support	South Africa
[84]	Grid-Connected PV System, Two-Stage Inverter, Multimode Control, MATLAB/Simulink, Hardware Prototype	FRT, Real & Reactive Power Control, Grid Stability Support	NA
[85]	PV Inverters, Non-Synchronous Power Generating Modules	Compliance Verification, Operational Requirements, PQ & Reliability	Czech Republic
[86]	ESS, Neural Network-Based Control, IEEE 39-Bus Test System	Frequency Regulation, Frequency Grid Code Compliance	NA
[87]	Four-Wire Multi-Source MGs, Grid-Forming (GFM) Inverters, Fractional-Order Sliding Mode Control	LVRT, Reactive Power Injection, PQ Requirements	Germany, Denmark
[88]	Wave Energy Converters, Wave Energy Park, ESS, Real-Time PHIL (Simulink, HIL)	Flicker, Harmonic Distortion, Voltage Variations (IEC 61000-4-15)	Sweden
[89]	PV Power Plant (20 MWp), ESS (Li-ion: LFP & NMC), Degradation-Aware Modeling	Power Output Variability Limits, Grid Code Compliance via Energy Storage	NA
[90]	Grid ESSs (especially Li-ion ESS)	Energy Storage Codes & Standards, Safety Requirements, Standardization Gaps	NA
[91]	ESSs, DC-Link Control, Dual Control with Positive Droop	FRT, Unbalanced Fault Compliance, Active & Reactive Current Control	Germany
[92]	RPPs, Unit-Level Testing + Plant-Level Simulation	PQ Test, Control Performance Test, LVRT, Voltage/Frequency Response, Anti-Islanding Protection	NA

NA: not available.

In this regard, the general structure and scope of the study are presented in Figure 2, which illustrates the logical flow of the research. The study begins with an overview of

global trends in renewable energy and ESSs, followed by a comprehensive comparative analysis of grid code regulations applied in different countries. Subsequently, the technical requirements imposed on inverter-based RPP and ESS are systematically examined, and critical regulatory gaps are identified. Based on this analysis, future-oriented and technically justified recommendations are developed for the Turkish Electricity Grid Regulation. This structured approach enables the study to address regulatory, technical, and operational aspects within a coherent and integrated framework.

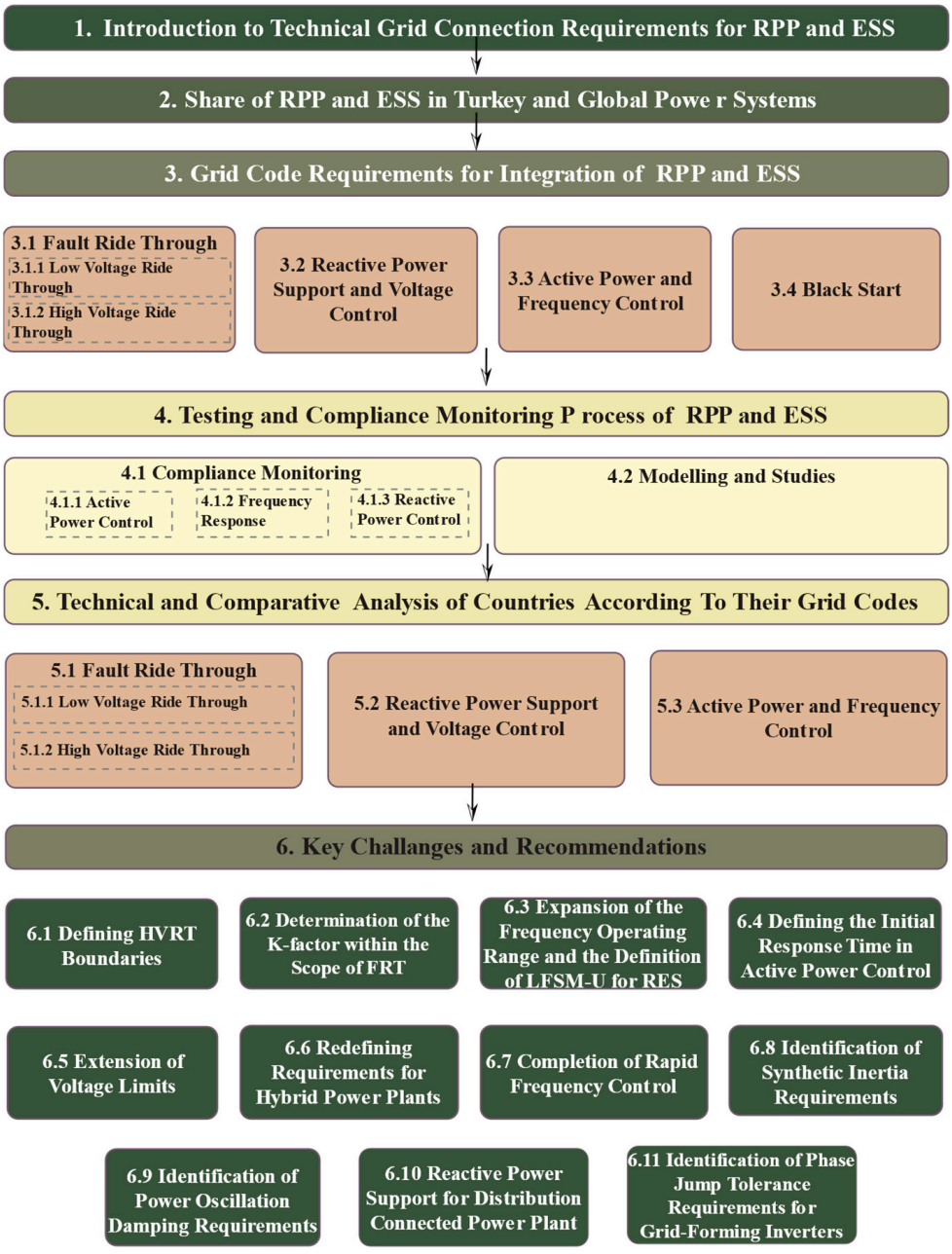

Figure 2. Structure of this paper.

The main contributions of this study can be summarized as follows:

- A comparative analysis of the Turkish Electricity Grid Code with selected international grid codes is conducted, focusing on requirements applicable to RPPs and ESSs.
- Unlike most previous studies that predominantly address RPP-oriented grid code compliance, this work explicitly incorporates ESSs as standalone and hybrid power

plant (HPP) components, providing a more comprehensive perspective on inverter-based generation and storage integration.

- Beyond regulatory definitions, the study systematically examines grid code compliance assessment practices, including monitoring, testing, and simulation-based verification methodologies, based on existing literature and technical reports.
- Specific to the Turkish Electricity Grid Code, technical limitations and missing provisions related to inverter-based generation and ESS integration are identified, and practically implementable revision and improvement recommendations are proposed.
- The study presents a future-oriented perspective for Türkiye, evaluating international best practices and emerging requirements, such as synthetic inertia, fast frequency response (FFR), power oscillation damping (POD), and HVRT, to support secure and reliable grid operation under high renewable and energy storage penetration.

While the contributions outlined above clarify the scope and novelty of this study, it is equally important to explicitly articulate the analytical questions that guide the comparative assessment. In order to avoid a purely descriptive review of grid code provisions and to establish a structured problem-oriented framework, the following research questions are formulated:

- What structural and technical gaps exist in the current Turkish Electricity Grid Regulation when benchmarked against leading international grid code frameworks and advanced regulatory practices, particularly in emerging areas such as HVRT, FFR, synthetic inertia, and ESS-specific performance criteria?
- How do different national grid codes parameterize and enforce dynamic performance requirements-such as LVRT/HVRT envelopes, reactive current injection (K-factor), post-fault active power recovery, and frequency-sensitive operating modes (LFSM-U, LFSM-O, FSM)-under increasing inverter-based resource penetration?
- What best practices can be identified in international compliance verification frameworks, including modeling requirements, simulation-based validation, monitoring architectures, and on-site testing methodologies?
- How can these international best practices be systematically adapted to strengthen the resilience, transparency, and future-readiness of the Turkish grid code in a high-renewable and storage-integrated power system?

Additionally, Figure 3 summarizes the systematic review approach followed in the study. The figure shows the databases used, search keywords and query strings, inclusion/exclusion criteria, and the thematic categorization of the literature into topics such as FRT capability, frequency control, reactive power support, compatibility tests, and ESS-specific requirements. This systematic approach demonstrates that the study is based on a comprehensive review methodology, strengthening the scientific validity of the analyses presented.

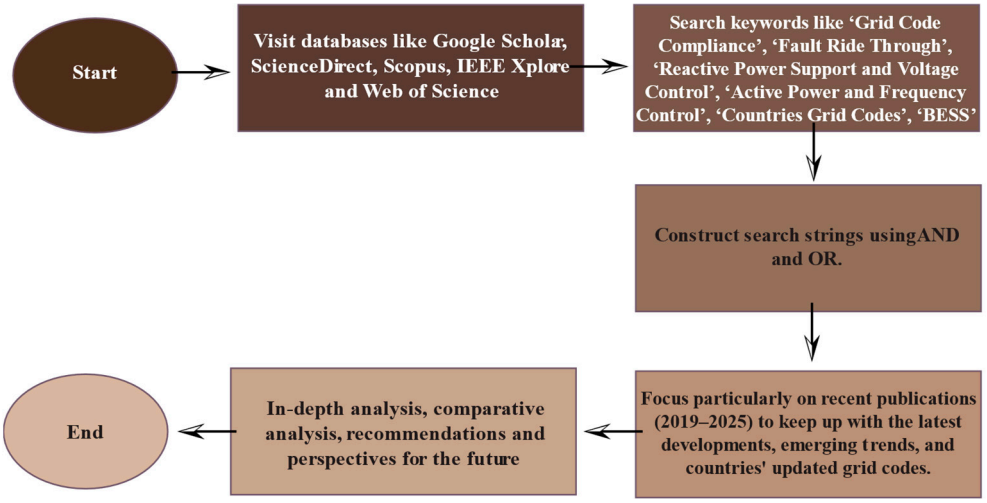

Figure 3. Flow chart of review methodology.

2. Share of RPP and ESS in Türkiye and Global Power Systems

Low carbon emission targets and clean energy policies are becoming increasingly decisive in reshaping modern power systems. Within this transformation, both the installed capacity and the share of RESs in total electricity generation are continuously increasing, making renewables a fundamental component of national energy portfolios worldwide [93–95]. The rapid development of renewable energy technologies and declining investment costs support sustainable energy.

While the rapid development of renewable energy technologies and declining investment costs support sustainable energy supply and reduce dependence on fossil fuels, the variable and intermittent nature of solar and wind generation introduces new operational challenges. In particular, increasing variability in generation profiles intensifies the need for flexibility, balancing capability, and system stability, highlighting the strategic role of ESS in modern power systems [96]. Among available storage technologies, BESSs have emerged as the dominant solution due to their modular structure, decreasing costs, and millisecond-level response capabilities [97]. In parallel, hybrid energy systems combining multiple renewable sources are increasingly adopted to further enhance system flexibility and operational robustness [98].

At the global scale, by the end of 2024, global renewable power capacity reached 4448 GW, with solar energy leading at 1865 GW, followed by hydropower (1283 GW) and wind energy (1133 GW). As illustrated in Figure 4, solar and wind power dominate the global renewable generation mix and together accounted for 96.6% of net renewable capacity additions in 2024, reflecting the rapid expansion of IBRs. In 2024 alone, total renewable capacity increased by 585 GW (15.1%), marking the highest annual growth on record, primarily driven by solar (452 GW) and wind (113 GW) installations [99]. These global deployment trends have directly influenced national energy policies, prompting countries to align long-term capacity planning with the increasing dominance of inverter-based renewable generation. Within this global transition context, Türkiye has defined ambitious renewable energy and capacity expansion targets in its long-term policy documents. According to the 12th Development Plan (2024–2028), the total installed power capacity of Türkiye is targeted to reach 136 GW by 2028, with wind and solar capacities planned to reach 18 GW and 30 GW, respectively. Within the same framework, the share of RESs in total electricity generation is expected to reach 50% by 2028 [100]. Furthermore, the National Energy Plan published by the Ministry of Energy and Natural Resources projects that the total installed power capacity of Türkiye will increase to 149.1 GW by

2030 and 189.7 GW by 2035, with wind and solar installed capacities reaching 29.6 GW and 52.9 GW, respectively [101]. Figure 5 illustrates the current installed solar and wind capacities of Türkiye [5,102,103], while Figure 6 presents capacity projections for the 2025–2035 period [100]. These projections indicate a substantial increase in inverter-based generation penetration within the Turkish power system, highlighting the growing importance of flexibility-oriented solutions such as ESSs.

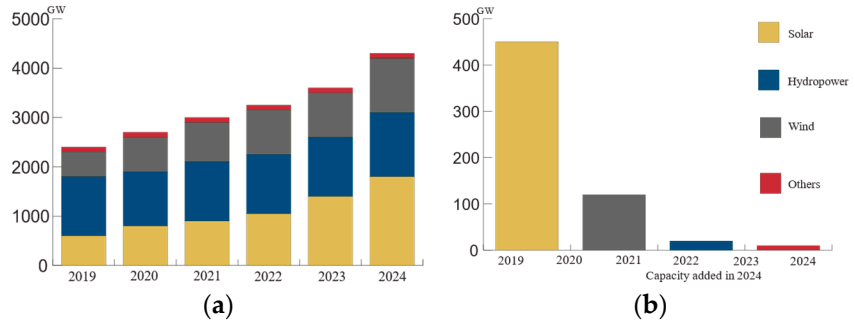

Figure 4. (**a**) Evolution of global renewable power capacity by technology between 2019 and 2024; (**b**) technology-wise renewable capacity addition in 2024 [99].

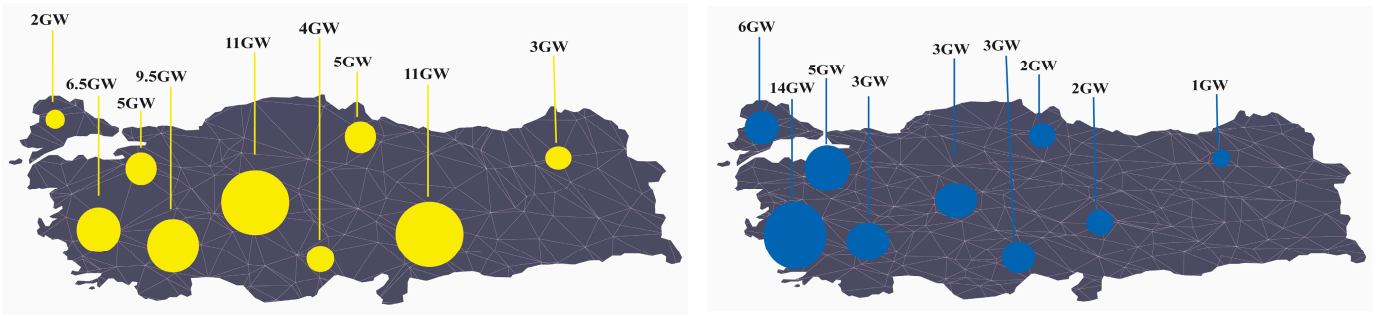

Figure 5. Current installed (**a**) solar and (**b**) wind power capacities of Türkiye [5,103].

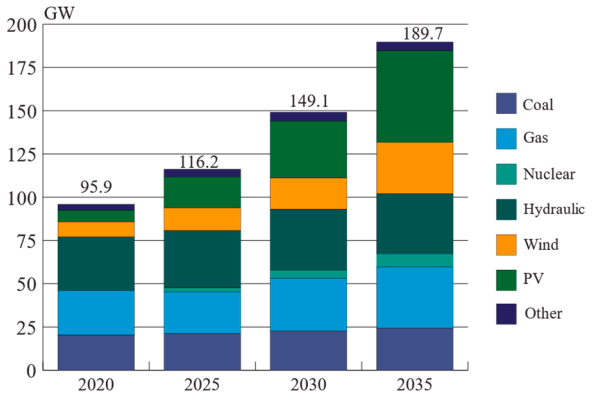

Figure 6. Capacity forecast of Türkiye for the period 2025–2035 [100].

Operational data further demonstrates that this transformation is already reflected in system behavior. Total annual electricity consumption increased from 328.8 TWh in 2021 to 354.6 TWh in 2025, while the share of wind and solar generation rose from approximately 13.3% to over 21% during the same period [104]. As the share of non-synchronous generation grows, system operating conditions increasingly depend on coordinated frequency support, voltage regulation, and balancing mechanisms. A representative example occurred during the Eid holiday period on 6 June 2025, when system demand declined

markedly and approximately 22.5 GWh of wind generation was curtailed within a short time window due to low load conditions. Such operational events reflect the sensitivity of high-renewable systems under reduced demand scenarios and emphasize the need for clearly defined voltage withstand requirements, structured frequency support functions, reactive power coordination, and appropriately integrated ESS solutions within the Turkish regulatory framework.

Consistent with these policy targets, the acceleration of renewable energy investments, particularly in solar and wind generation, has made the need for grid flexibility more pronounced and elevated the strategic importance of ESS within national energy planning. The planned expansion of battery storage infrastructure is expected to facilitate renewable integration, enhance operational reliability, and strengthen supply security.

In this context, the allocation of connection points for behind-the-meter, generation-integrated, and standalone storage facilities by the transmission system operator (TEİAŞ, Ankara, Türkiye) plays a critical role in ensuring secure and efficient system operation [105,106]. Planning processes must also jointly consider investment costs, system-level contributions, and end-of-life management of storage technologies [107].

The strengthened carbon reduction target of Türkiye of 41% by 2030, together with national energy planning documents, further reinforces the role of energy storage in supporting high renewable penetration. The National Energy Plan forecasts a storage capacity of 2.1 GW/4.2 GWh by 2030 and 7.5 GW/15 GWh by 2035, alongside substantial increases in wind and solar installed capacity [100]. These targets underline the growing need for flexibility-oriented technologies such as ESS, grid-forming inverters, demand-side participation, and advanced distributed generation management, supported by digitalization and cybersecurity enhancements in energy systems [108,109].

Similar dynamics are also observed at the global scale. Worldwide, the growing share of renewable energy has driven a rapid expansion of battery energy storage deployments as a key flexibility and balancing resource in power systems with high renewable penetration [110–112]. Declining battery costs, evolving market structures, and time-of-use pricing mechanisms have accelerated global BESS investments, with approximately 40 GW of new battery capacity commissioned in 2023 alone [113]. As illustrated in Figure 7, the majority of this capacity consists of grid-scale projects, reinforcing the strategic role of ESS in long-term power system planning.

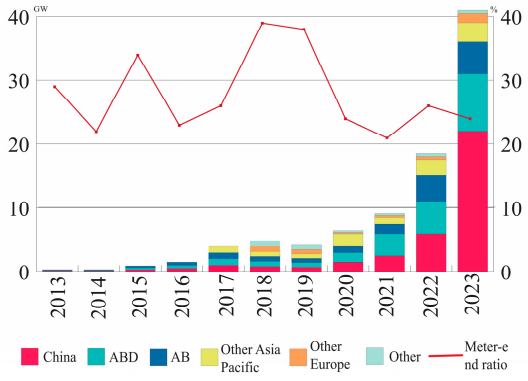

Figure 7. Global distribution of annual ESS capacity increases in the electricity sector [5].

At the international level, the multi-service capability of ESS has reshaped operational and market participation strategies across different regions. In the USA, BESS applications are primarily deployed to support frequency control and system stability, contributing effectively to both primary frequency control and fast frequency reserve services [114,115]. Similarly, transmission system operators in Sweden, Ireland, and the UK increasingly rely on batteries to provide FFR and other ancillary services under high renewable penetration

conditions [116]. Growth trends in the European energy storage market further confirm this development, with annual installed capacity increasing from 0.6 GWh in 2015 to 9.4 GWh in 2022, predominantly within European Union member states [117].

The rapid expansion of ESS deployment has also been reflected in strategic industrial and policy frameworks. The European Union's objective of transitioning to zero-emission new light-duty vehicle sales by 2035 necessitates a substantial increase in battery manufacturing capacity, which is projected to reach 458 GWh by 2025 and 1083 GWh by 2030 [118,119]. Figure 8 highlights the geographical distribution of storage technologies, indicating that while mechanical storage solutions are widely dispersed, chemical storage technologies are primarily concentrated in countries such as France and Germany [116,120]. These patterns demonstrate that storage technologies fulfill different roles depending on regional energy policies, market structures, and supply security considerations.

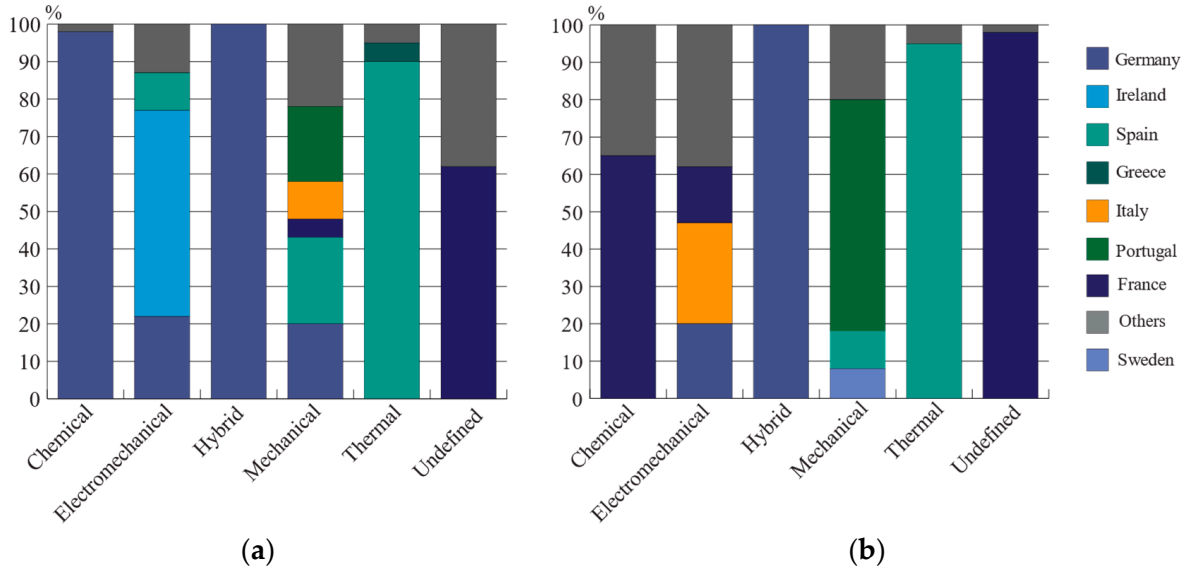

Figure 8. Specific relative distribution of individual technologies [116]: (**a**) installed power and (**b**) installed capacity.

3. Grid Code Requirements for Integration of RPP and ESS

RPPs and ESSs must comply with a wide range of grid code requirements to ensure stable and reliable operation in modern power systems with high renewable energy penetration. These requirements typically encompass dynamic fault performance, voltage regulation capability, active and reactive power control, and system restoration functionalities. As illustrated in Figure 9, grid code obligations applicable to RPP and ESSs can be classified into four main categories: Fault Ride-Through (LVRT/HVRT), Reactive Power Support and Voltage Control, Active Power and Frequency Control (LFSM, LFSM-O, LFSM-U), and Black Start capability. This structured classification provides a systematic basis for evaluating the technical expectations imposed on renewable generation and storage facilities and highlights the growing need for consistent and well-defined performance standards under diverse grid operating conditions.

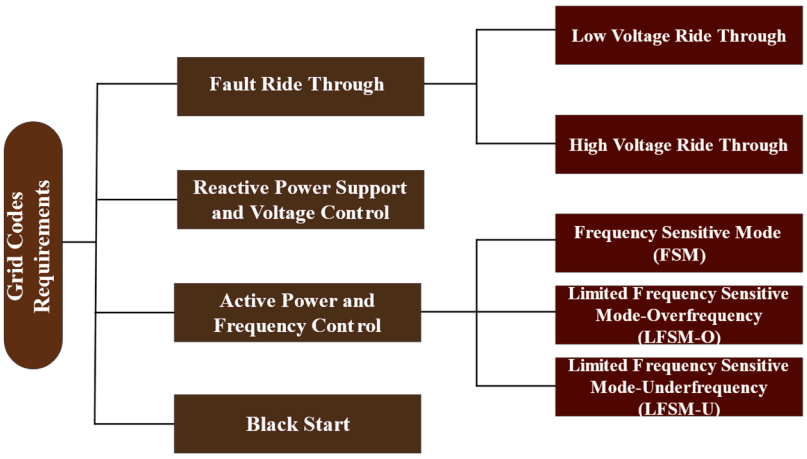

Figure 9. Classification of grid code requirements.

3.1. Fault Ride Through

FRT refers to the ability of power generation facilities connected to the power system to continue operating without disconnecting from the grid during short-term voltage dips, swells, or fault conditions caused by short circuits [121]. This requirement, which is critical for grid stability, is particularly important for IBRs and ESSs, since IBRs and ESS units without FRT capability can pose serious risks to stability and safety in systems with high renewable energy generation [122]. Therefore, grid codes define FRT requirements in accordance with national and international standards, including IEEE 1547 [123], IEEE 2800 [124], and ENTSO-E regulations [125].

FRT requirements are defined based on three fundamental performance criteria to ensure that RPPs and ESSs remain connected to the grid during fault conditions and actively support overall system stability. First, the grid connection criterion requires generation units to remain connected to the grid and operate for a predefined period depending on the type and duration of the fault [126]. Second, the active and reactive power contribution criterion requires IBRs and ESSs to provide active and/or reactive current within specified limits to support the grid during the fault duration [127]. The third criterion, return to normal operation, requires facilities to return to pre-fault conditions in accordance with specified dynamic response characteristics after the fault has been cleared [128]. These three fundamental elements form the basic framework for the contribution of FRT performance to both grid security and the stable integration of RESs.

FRT performance is generally evaluated under two categories [129]. LVRT refers to a facility's ability to remain connected to the grid during voltage dips and provides the required reactive power support, while HVRT similarly mandates continued operation during voltage surges, including appropriate voltage and reactive power support, without disconnection from the grid. These capabilities enable inverter-based generation technologies to respond quickly and safely to fault conditions, directly contributing to both grid voltage stabilization and overall system security.

3.1.1. Low-Voltage Ride-Through

LVRT is a core grid code requirement related to the ability of ESSs to comply with grid support obligations during voltage dips caused by faults or short-circuit events [130,131]. A generic LVRT capability curve commonly adopted in international grid code practices is illustrated in Figure 10a. Although detailed voltage–time thresholds differ among countries, the overall structure and intent of LVRT requirements are largely consistent, reflecting a common international framework for FRT behavior [132]. Under LVRT conditions, grid-connected facilities are required to remain connected down to predefined voltage

levels without protection tripping and to support the grid, which is particularly critical for maintaining transmission-level stability [133,134].

In the Turkish Electricity Grid Regulation [135], LVRT requirements are explicitly defined in Annex-18, and the corresponding national LVRT characteristic is shown in Figure 10b. According to this regulation, when the phase-to-phase voltage at the connection point remains within Area 1 and 2 of the LVRT curve, generation facilities must remain connected during voltage dips affecting one or all phases. For Area 1 voltage dips, the active power output must be restored after fault clearance at a ramp rate of at least 20% of the nominal active power per second, whereas for Region 2, a lower recovery rate of at least 5% per second is permitted.

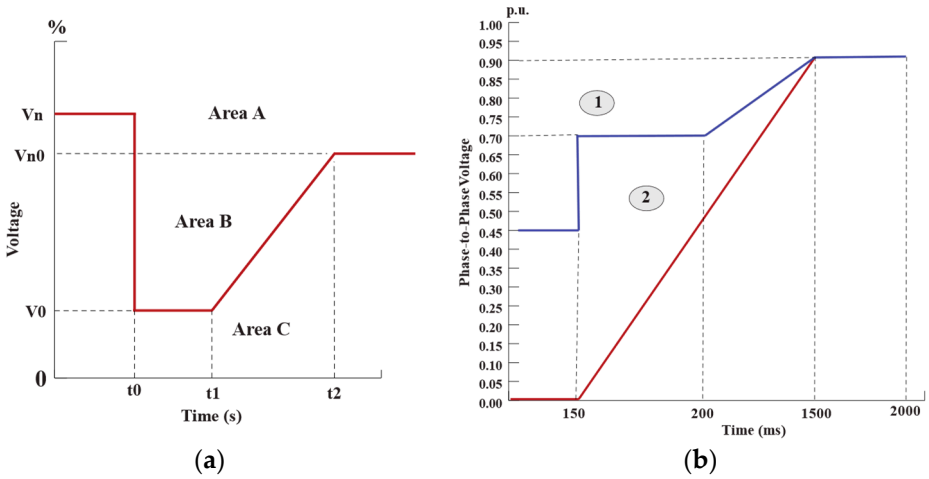

Figure 10. (**a**) FRT/LVRT curve [136]; (**b**) Turkish grid code LVRT requirement curve [135].

Under normal operating conditions, PCC voltage variations within ±10% (0.9 p.u.–1.1 p.u.) are acceptable. During fault conditions exceeding this range, wind turbine generators and PV inverters are required to provide inductive or capacitive reactive current support up to 100% of the nominal current capacity without exceeding transient ratings. As specified in Annex-18, this reactive current must be reached within 60 ms (±10% tolerance) and sustained for at least 1.5 s to support voltage recovery. Recent grid code developments further indicate that similar reactive current support principles are increasingly extended beyond LVRT to include HVRT scenarios, ensuring voltage stability under a wide range of disturbances [137,138].

3.1.2. High-Voltage Ride-Through

HVRT is a critical grid operation requirement that refers to the ability of energy facilities, particularly power electronics-based sources such as inverter-based generation units and ESS, to remain connected to the grid during sudden voltage surges and contribute to system stability [139]. Under HVRT requirements, facilities are expected to prevent the unnecessary triggering of protection systems under overvoltage conditions, continue to operate within specified upper voltage limits, and contribute to voltage regulation by providing reactive current support when necessary. Figure 11 presents a typical HVRT voltage–time characteristic curve [140,141]. This capability is of great importance in limiting the propagation effects caused by overvoltage at both transmission and distribution levels and in maintaining system reliability.

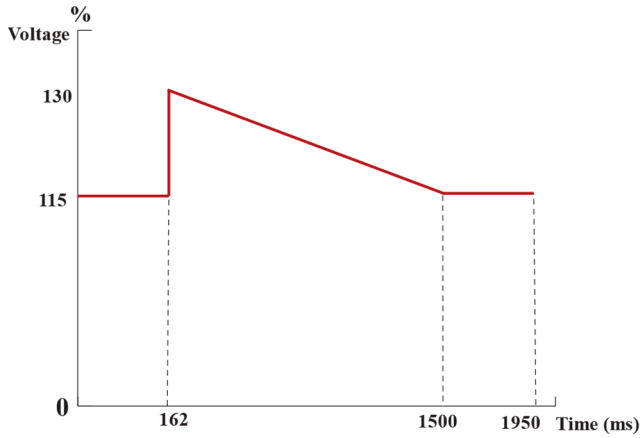

Figure 11. HVRT standard curve of IEC 61400-21-1 [140,141].

Unlike LVRT requirements, the Turkish Electricity Grid Regulation does not explicitly define detailed technical performance criteria for HVRT. However, international experience clearly demonstrates that HVRT capability is a critical function for modern power systems with high penetration of inverter-based renewable generation and storage resources. The Iberian Peninsula blackout report published by Red Eléctrica highlights that, under overvoltage conditions, insufficient reactive current contribution from IBRs can significantly weaken voltage control and adversely affect system restoration processes [142]. This finding underscores the importance of explicitly addressing HVRT performance within grid codes to avoid large-scale stability issues during overvoltage events.

3.2. Reactive Power Support and Voltage Control

Maintaining voltage within operating limits is a fundamental requirement for reliable power system operation and equipment protection [143]. Since voltage regulation is inherently dependent on reactive power management, the capability of RPPs and ESSs to supply or absorb reactive power constitutes a critical component of grid stability [144]. Accordingly, grid codes impose reactive power obligations on IBRs, with specific requirements varying according to connection level, operating mode, and system conditions.

In generation-integrated storage configurations, reactive power responsibilities are defined by both the operational status of the primary generation unit and the limits specified in the Turkish Electricity Grid Regulation. When the primary generation source is in service, reactive power provision must comply with the technical characteristics of the relevant generation technology and the boundaries defined in Annex 18. However, when the main generation unit is unavailable or when the active power output falls below 10% of the installed capacity, reactive power support must be provided exclusively by the storage unit [145]. This operational arrangement ensures continuity of voltage support under varying generation conditions and enhances system robustness.

To meet these obligations, inverter-based systems employ different reactive power control strategies. Among these, power factor control and Volt-VAR control are the most adopted approaches [146]. Power factor control regulates reactive power output based on a predefined relationship with active power flow, whereas Volt-VAR control enables a voltage-dependent response by continuously adjusting reactive power according to measured grid voltage levels [147]. A representative Volt-VAR characteristic, illustrating voltage deadband regions, maximum reactive power limits, and slope definitions associated with inverter capacity, is shown in Figure 12 [148]. By dynamically adapting reactive power output to local voltage conditions, this control strategy effectively mitigates voltage deviations and improves voltage profiles across both transmission and distribution networks. Recent studies on advanced inverter-based control architectures, including fuel-cell-integrated

active filtering systems, further demonstrate that robust harmonic suppression and fast dynamic response significantly enhance voltage regulation performance under distorted and sag/swell grid conditions [149].

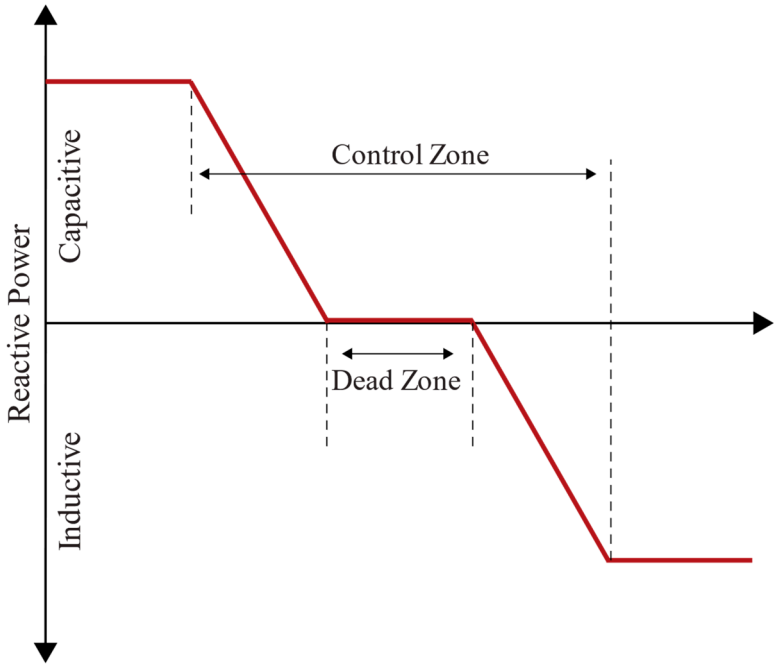

Figure 12. Volt-VAR curve [148].

Maintaining the voltage at the point of common coupling within predefined limits requires IBRs to reserve sufficient reactive power capability to support voltage regulation and system stability [150]. Under nominal operating conditions, grid voltage is typically maintained within a narrow band (e.g., 0.95 p.u.–1.05 p.u.). When deviations occur, IBRs are expected to inject or absorb reactive power to counteract voltage changes; for example, reactive power absorption is required when the PCC voltage rises above its nominal value. This response is governed by a predefined voltage-reactive power characteristic with a specified droop, ensuring coordinated and predictable voltage control.

According to the ENTSO-E Network Code on Requirements for Generators [151], which underpins grid code practices in many European countries, the Volt-VAR droop is typically defined within the range of 2–7%. In the Turkish Electricity Grid Regulation, these principles are implemented through defined droop characteristics and associated dynamic performance criteria, including response time, settling time, and steady-state error limits. Together, these requirements ensure that inverter-based generation and storage systems contribute effectively to voltage regulation while maintaining overall system coordination and stability. In the Turkish Electricity Grid Regulation, reactive power and voltage control performance are evaluated at the PCC, where compliance is coordinated through the plant controller and verified within defined tolerance bands during commissioning and monitoring procedures.

3.3. Active Power and Frequency Control

RPPs are required to comply with active power control requirements defined in grid codes to support frequency stability, limit power ramps, and ensure coordinated system operation under normal and disturbed conditions [152]. These requirements typically include active power curtailment, ramp-rate limitation, frequency-dependent power response, and setpoint-based active power regulation, enabling the secure integration of variable renewable generation into the power system [153].

ESSs, in contrast to renewable generation units, inherently enable bidirectional active power flow, allowing them to both inject power into the grid and absorb power from it [154]. This characteristic requires ESSs to support system stability under both generation and consumption conditions [13,155]. Consequently, active power control requirements for ESSs must address not only power injection scenarios but also power withdrawal operation [156], enabling ESSs to contribute to system stability in both directions of power flow. In accordance with the Turkish Electricity Grid Regulation, ESSs are required to continuously and automatically regulate their active power levels in line with target values transmitted by the system operator [145]. Safe transitions between charging and discharging modes are essential to prevent adverse grid impacts caused by sudden power variations. For this reason, active power control must be initiated from the zero-power level during all transition processes, while control accuracy must be maintained throughout operation. Power level deviations are required to remain within ± 1 MW or $\pm 1\%$ of the installed capacity. In addition, limiting ramp rates and enforcing maximum power change constraints are recognized as effective measures for mitigating sudden load variations and enhancing system stability during dynamic operating conditions. The literature further indicates that controlled active power–time behavior, coordinated with system operator commands, plays a key role in reducing the impact of rapid power fluctuations on grid performance.

In terms of frequency control, the active power frequency response of RPP and ESS is defined by their ability to automatically respond to deviations in system frequency [157]. In this context, frequency response is addressed under three basic operating modes [158,159]:

1. Frequency Sensitivity Mode—Underfrequency (LFSM-U): When the system frequency falls below the treshold value, the ESS should limit the frequency drop by increasing the active power output to the extent of its available capacity.
2. Frequency Sensitivity Mode—Overfrequency (LFSM-O): When the system frequency rises above the treshold value, the ESS should respond to the frequency rise by reducing its active power output.
3. Frequency Sensitivity Mode (FSM): The ESS should continuously monitor frequency deviations to support grid frequency stabilization and contribute to maintaining dynamic stability.

While WPPs and SPPs typically apply generation curtailment only during overfrequency events, ESSs can contribute more effectively to system balancing by switching from charging to discharging during frequency drops and from discharging to charging during frequency increases, owing to their bidirectional power flow capability. Within the current Turkish Electricity Grid Regulation, frequency response requirements are explicitly limited to the definition of the LFSM-O mode, whereas LFSM-U and continuous FSM response modes are not formally specified.

3.4. Black Start

Black Start refers to the process of re-energizing the power grid in the event of a widespread or complete collapse [160]. In this process, power plants that can operate independently without requiring an external energy source are brought online first to supply energy to the grid. Other power plants are then gradually connected to the system; frequency and voltage synchronization are critical during this phase. To maintain system stability, energy flow is managed in a controlled and phased manner during Black Start operations, preventing sudden power fluctuations [161].

ESSs, particularly GFM-controlled types, play a critical role in black start scenarios due to their fast dynamic response and ability to generate an independent voltage/frequency reference. Unlike grid-following (GFL) inverters, GFM-ESSs can stabilize both voltage

and frequency after a system collapse, accelerate system recovery, and enable the safe commissioning of other generation facilities [162].

4. Testing and Compliance Monitoring Process of RPP and ESS

4.1. Compliance Monitoring

In this context, grid code compliance tests are applied to verify whether both RES and ESS facilities meet certain technical requirements [30]. Grid codes standardize the voltage, frequency, active, and reactive power behavior of generation and storage units, enabling system operators to manage energy from different sources safely and reliably [163]. These requirements cover compliance with national legislation as well as international grid regulations such as ENTSO-E [164].

4.1.1. Active Power Control

The compliance monitoring process for RPPs and ESSs constitutes a systematic verification phase aimed at ensuring that grid-connected facilities operate within the technical and operational limits defined by applicable grid codes and regulations [165]. During this process, monitoring activities focus on assessing whether the plant correctly follows active and reactive power control commands, respects predefined operating limits, and maintains stable operation across different operating modes [166,167].

In accordance with grid code monitoring provisions, the first stage involves verifying active power control behavior [168]. This includes monitoring compliance with maximum export and import limits, accurate tracking of transmitted setpoints, adherence to ramp-rate constraints, and proper activation or deactivation of control modes as required by the system operator. Within this framework, ESSs are required to automatically regulate the difference between the current active power level and the dispatched power reference based on control signals issued by the system operator. Accordingly, ESSs are expected to adjust their active power output accurately, rapidly, and bidirectionally in both charging and discharging modes, ensuring compliant active power control under varying operating condition [75]. For hybrid configurations, it is also verified that active power contributions from RPPs and ESSs are coordinated and that control commands are executed without undesired interactions between generation and storage units [169].

From a regulatory perspective, national grid codes explicitly define active power control monitoring requirements for both generation and storage assets. In the European Union, the ENTSO-E Requirements for Generators [170] mandate continuous monitoring of active power output, verification of ramp-rate compliance, and accurate execution of dispatched setpoints. Similar provisions are adopted in Germany under VDE-AR-N 4110 [171] and VDE-AR-N 4120 [172], where compliance monitoring includes supervision of active power gradients and coordinated control at the point of common coupling for hybrid plants. In the UK, the ENA Engineering Recommendation G99 requires Type C and Type D generating units, explicitly including electricity storage systems, to demonstrate controlled active power behavior during normal operation and system events, with particular emphasis on ramp-rate compliance and interaction with frequency response functions [173]. Nordic regulations similarly emphasize monitoring of active power gradients and stable post-disturbance power recovery, ensuring predictable system balancing without oscillatory behavior, while Australia adopts comparable monitoring requirements for bidirectional ESS operation [174]. Within the Turkish Electricity Grid Regulation [135], compliance monitoring of active power control is technically focused on verifying accurate setpoint tracking, ramp-rate conformity, and stable execution of frequency-sensitive active power functions at the point of connection, including coordinated power sharing between RPPs and ESSs in hybrid plant configurations.

A subsequent monitoring stage focuses on the continuous supervision of system operating states and availability [175]. For RPPs, this includes tracking real-time power output, availability status, and operational limits, while for ESSs it involves monitoring charge and discharge states, available energy, and usable capacity [13]. Monitoring systems are required to confirm that both generation units and storage modules operate above their minimum technical thresholds and remain within permissible operating ranges defined by the regulation [176,177]. During monitored operation and test sequences, system responses to different setpoints, ramp rates, and output transitions are evaluated to ensure stable behavior, controlled power recovery, and compatibility with grid operation [177]. Overall, these monitoring stages provide evidence that RPPs and ESSs can reliably support grid operation and comply with regulatory performance requirements under normal operating conditions.

4.1.2. Frequency Response

Grid codes require frequency response capabilities of both RPPs and ESSs to be explicitly verified through structured compliance monitoring and testing procedures [178]. In the European Union, the ENTSO-E RfG mandate that Power Park Modules demonstrate Limited Frequency Sensitive Mode (LFSM-U and LFSM-O) and FSM performance through predefined test sequences, including frequency step and ramp injections, verification of droop settings, response delays, and stability during activation [170]. Similarly, the UK's ENA Engineering Recommendation G99 requires Type C and Type D power generating modules, explicitly including electricity storage, to undergo frequency response tests that assess response magnitude, activation time, repeatability, and coordination with plant-level controllers, with results documented as part of the commissioning and final operational notification process [179]. In Nordic countries, such as Finland, frequency response compliance for grid ESSs is evaluated through staged verification procedures combining simulations and commissioning measurements, ensuring correct activation of LFSM functions, droop accuracy, and stable operation under frequency disturbances [180]. In Türkiye, frequency-related requirements are defined in Annex-18 of the Turkish Electricity Grid Regulation. LFSM-O is mandatory for RPPs, while ESSs are required to comply with both LFSM-O and LFSM-U provisions. Transmission-connected ESSs with an installed capacity exceeding 30 MW may additionally participate in ancillary services through FSM. For ESSs participating in FSM-based ancillary services, compliance monitoring focuses on verifying correct FSM activation, adherence to defined slope characteristics, and coordinated operation at the grid connection point. However, explicit response time requirements and dynamic stability margins are not formally specified [135].

Within these regulatory frameworks, compliance monitoring focuses on verifying that both RPPs and ESSs follow frequency-triggered active power trajectories without violating converter current limits, export/import constraints, or plant-level coordination rules [181]. Test procedures assess whether frequency response functions are activated within specified time limits, whether droop characteristics remain within adjustable ranges defined by the system operator, and whether stable operation is maintained throughout the response period [167]. For ESSs, additional monitoring verifies correct bidirectional behavior, ensuring seamless transitions between charging and discharging modes during over and under-frequency events [182], while for RPPs the focus remains on controlled power reduction or increase within available capacity limits [183]. Accordingly, frequency response compliance is verified through on-site measurements and model-based validation, ensuring predictable and reliable frequency support from IBRs under grid code requirements [184].

4.1.3. Reactive Power Control

Grid codes require the reactive power control capabilities of RPPs and ESSs to be continuously monitored and verified to ensure voltage regulation and system stability at the grid connection point [185]. Under the ENTSO-E RfG, Power Park Modules are required to demonstrate compliant reactive power behavior through predefined operating modes, including fixed power factor control, reactive power setpoint control, and voltage-dependent Volt-VAR control [151]. Compliance monitoring focuses on verifying that the delivered reactive power remains within the specified capability envelope, respects defined deadband limits and follows the commanded setpoints or characteristic curves without violating converter current constraints or plant-level coordination rules [186].

Similar monitoring requirements are implemented in national grid codes derived from the RfG [187]. In the UK, the ENA Engineering Recommendation G99 requires Type C and Type D generating units, explicitly including electricity storage systems, to provide continuous reactive power control capability and to demonstrate compliance through monitored operation at the point of common coupling [179]. Monitoring activities verify correct execution of Volt-VAR characteristics, adherence to reactive power response slopes, and stable operation during voltage variations. In Nordic countries, such as Finland, reactive power compliance monitoring for both generation and storage assets combines operational measurements and commissioning verification to confirm accurate tracking of voltage-dependent reactive power functions, droop accuracy, and absence of sustained oscillations during normal and disturbed voltage conditions [188].

Within the Turkish Electricity Grid Regulation, reactive power control obligations are defined for both RPPs and ESSs with respect to voltage regulation at the grid connection point [135]. Compliance monitoring under the Turkish Electricity Grid Regulation focuses on verifying that IBRs provide requested inductive or capacitive reactive power support within defined operating limits and response time, follow voltage-dependent reactive power control characteristics, and maintain coordination between generation and storage units in hybrid configurations. Monitoring activities confirm that reactive current contributions remain within permissible converter ratings and that voltage regulation support is sustained during steady-state operations and during LVRT events involving short-duration voltage deviations beyond the normal operating band.

Across all these regulatory frameworks, compliance monitoring of reactive power control relies on continuous operational data, disturbance records, and model-consistent measurements to demonstrate that RPPs and ESSs can deliver predictable, stable, and regulation-compliant voltage support [189]. This approach ensures that IBRs contribute effectively to voltage control objectives while maintaining coordinated operation at plant and system levels in accordance with national grid code requirements.

4.2. Modeling and Studies

Modern grid codes increasingly rely on mandatory modeling and simulation-based studies as a primary mechanism for verifying the compliance of RPPs and ESSs [190]. With the growing penetration of IBRs, regulatory authorities no longer consider static capability declarations sufficient; instead, they require validated dynamic models to demonstrate compliant behavior under a wide range of operating and disturbance conditions [191]. These modeling requirements aim to ensure predictable system response, coordination among multiple inverter-based units, and secure power system operation under both normal and stressed grid conditions [192].

Across many power systems, grid codes explicitly mandate the submission of plant-level dynamic models, typically including representations of inverter controls, plant controllers, protection functions, and grid interface characteristics [193,194]. These models are

required to capture active power control behavior (e.g., ramp-rate, frequency response, and power setpoint tracking), reactive power capability, and ride-through performance under voltage and frequency disturbances [177]. Compliance is generally demonstrated through predefined simulation studies, which assess plant behavior during events such as voltage dips, frequency deviations, fault clearance, and post-disturbance recovery. In Europe, this model-based compliance philosophy is harmonized through the ENTSO-E Network Code on Requirements for Generators [151,187]. The regulation requires Power Park Modules to provide validated dynamic models and to demonstrate compliance through standardized simulation test cases [188]. These requirements have been transposed into national grid codes across many countries, including Germany [171,172], Spain [56], the UK [173], France [195], Denmark [196], Sweden [197], Finland [180], and the Netherlands [173], where simulation studies form a mandatory part of grid connection approval. In these systems, both RMS and EMT-type models are commonly required depending on connection voltage level and system impact, and model validation against commissioning test results is emphasized to ensure consistency between simulated and measured behavior [198].

Similar modeling obligations are observed in non-European regulatory frameworks. In the USA, interconnection standards such as IEEE 1547-2018 [123], together with reliability requirements issued by NERC, require IBRs to provide validated dynamic models for system planning and operational studies, particularly under abnormal voltage and frequency conditions [199]. In Canada [200], grid codes and interconnection requirements defined by system operators such as IESO [201] and AESO [202] rely on plant-level models and simulation studies to assess voltage stability, frequency response, and FRT performance of renewable generation and ESS facilities. In Australia, the National Electricity Rules and Generator Performance Standards mandate detailed modeling and extensive dynamic simulation studies as part of the grid connection process, with compliance verified prior to final approval [203,204].

The Turkish Electricity Grid Regulation aligns with international practices by requiring modeling- and study-based verification of grid code compliance for renewable generation and ESS installations. The updated ESS regulation mandates multiple model representations, including static, RMS, and EMT models at both detailed and aggregated levels, with particular emphasis on aggregated RMS models based on standardized WECC/IEC control structures to accurately capture plant-level dynamic behavior in transmission system studies. In addition, analyses conducted using detailed RMS models are required to be reproducible, allowing independent validation of simulation results by the transmission system operator [135]. Dynamic simulation studies constitute a fundamental component of the grid connection and approval process, enabling the evaluation of active and reactive power control performance, frequency response behavior, and FRT capability under predefined disturbance scenarios [205]. Through these studies, regulatory authorities and system operators are able to assess plant-level compliance with grid code requirements in a manner consistent with internationally adopted verification and validation practices.

To provide a structured synthesis of the regulatory approaches discussed, Table 2 presents a comparative overview of key compliance monitoring and modeling framework elements across selected regions. The comparison focuses on dynamic model submission requirements, RMS and EMT modeling obligations, validation practices, on-site testing procedures, and the use of aggregated plant-level models. This overview clarifies common patterns and structural differences among national frameworks while avoiding evaluative ranking.

Table 2. Comparative summary of modeling and compliance requirements.

Region/Country	Mandatory Dynamic Model Submission	RMS Models Required	EMT Models Required	Model Validation Against Measurements	On-Site Compliance Testing	Aggregated/ Standardized Plant-Level Models
ENTSO-E [151,187]	Validated dynamic models required through standardized simulation test cases	RMS models required	EMT required depending on voltage level and system impact	Validation against commissioning tests emphasized	On-site testing considered essential	Harmonized framework with standardized modeling structures
Germany [171,172]	Transposed ENTSO-E modeling requirements	RMS models required	EMT required depending on connection level	Validation emphasized	Commissioning and testing procedures applied	Structured plant-level modeling aligned with ENTSO-E
UK [173]	Simulation studies mandatory for grid connection approval	RMS models required	EMT required for higher impact connections	Validation required prior to final approval	Formal commissioning and compliance tests required	Structured plant-level modeling framework
Nordic Countries [180,188]	Compliance evaluated through staged simulation and commissioning procedures	RMS-based verification applied	EMT applied depending on system impact	Validation through simulation and measurement comparison	Commissioning measurements required	No specific aggregated model structure stated
USA [123,199]	Validated dynamic models required for planning and operational studies	RMS modeling used for system studies	EMT applied under abnormal or high-impact conditions	Validation required	Testing applied during commissioning	Aggregated modeling framework varies by operator
Australia [203,204]	Generator Performance Standards mandate detailed modeling and dynamic studies	RMS models required	EMT required under performance assessment	Compliance verified prior to final approval	Extensive testing prior to approval	Structured modeling framework under performance standards
Türkiye [135]	Static, RMS, and EMT models required under updated regulation	RMS models required	EMT required	Reproducibility and validation required	Compliance monitoring and testing required	Aggregated RMS models required based on WECC/IEC structures

5. Technical and Comparative Analysis of Countries According to Their Grid Codes

5.1. Fault Ride Through

FRT capability constitutes one of the most critical technicals requirements imposed on inverter-based renewable generation and ESS in modern grid codes [206]. Across different countries, LVRT and HVRT requirements define the voltage–time operating envelopes,

current injection obligations, and post-fault recovery behavior expected from WPP, SPP, and ESS under grid fault conditions [207]. In this subsection, LVRT and HVRT requirements specified in selected international grid codes are comparatively analyzed with respect to voltage thresholds, fault duration tolerances, reactive current support obligations, and recovery criteria [208]. The analysis highlights converging technical practices as well as regulatory differences among countries, providing a structured basis for evaluating the adequacy of existing requirements and identifying gaps relevant to inverter-dominated power systems.

5.1.1. Low-Voltage Ride-Through

LVRT requirements constitute a fundamental compliance condition in the grid regulations of many countries, reflecting the critical role of inverter-based generation and ESSs in maintaining grid stability during fault conditions. LVRT directly affects system dynamic stability and post-fault recovery performance by defining the capability of facilities to remain connected to the grid and sustain operation during voltage depressions [209]. To enable an objective comparison among national regulations, this study focuses on four key LVRT parameters: minimum fault voltage (V_f), fault duration (T_f), recovery voltage (V_{af}), and recovery time (T_r). These parameters collectively characterize fault severity and recovery expectations, allowing country-specific requirements to be evaluated within a consistent analytical framework.

As inverter-based resources increasingly dominate generation portfolios, LVRT requirements have evolved from basic connection criteria to performance-based stability obligations that directly influence post-fault system recovery. In this context, understanding the relative stringency of LVRT parameters across jurisdictions is essential for evaluating how grid codes adapt to rising IBR penetration and reduced system inertia. Figure 13 presents a synthesized two-dimensional heat map illustrating relative LVRT stringency, where low V_f and long T_f values indicate more demanding requirements. By transforming country-specific voltage–time envelopes into a harmonized difficulty representation, the figure enables a structured assessment of regulatory evolution rather than a mere side-by-side presentation of national limits. To complement this visual comparison and enhance transparency, Table 3 provides a numerical summary of the LVRT parameters extracted from the corresponding national grid codes, forming the quantitative basis of the comparative assessment.

The comparative analysis reveals both convergence and differentiation in LVRT criteria across national grid codes. Specifically, the Turkish Grid Code permits operation down to V_f = 0.0 p.u. for a fault duration of T_f = 0.15 s, while the German and Danish grid codes impose identical fault-sequence requirements with V_f= 0.0 p.u. and T_f = 0.15 s. In contrast, the Spanish and Italian regulations define a higher minimum fault voltage of V_f = 0.2 p.u. combined with a longer fault duration of T_f = 0.5 s. In addition, recovery to nominal voltage levels within approximately three seconds after fault clearance is a commonly defined criterion. These trends indicate that LVRT requirements for inverter-based generation and storage technologies are becoming increasingly stringent, despite differences in network structure and operational conditions. As a result, advanced control algorithms, robust protection schemes, and resilient power electronic hardware are increasingly necessary for compliance. Post-fault active power recovery represents a further critical dimension of LVRT performance.

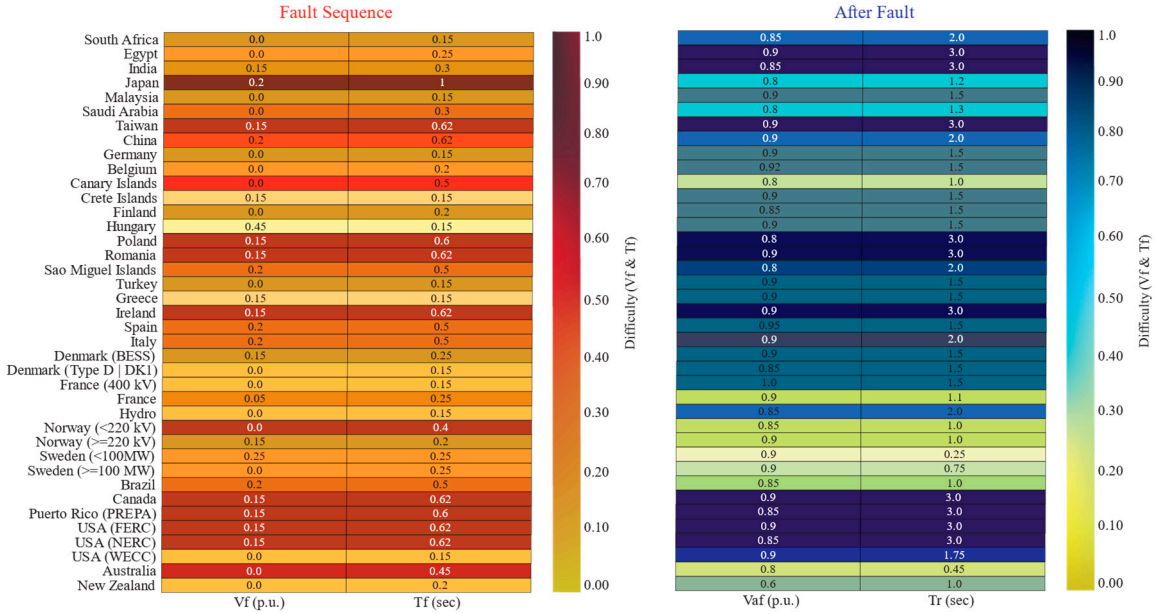

Figure 13. Comparative LVRT stringency across countries and its implications for evolving FRT performance standards. The data presented were compiled from references [136,145,152,180,209–224].

Table 3. Numerical summary of LVRT requirements across selected grid codes.

Region/Country	V_f (p.u.)	T_f (s)	V_{af} (p.u.)	T_r (s)	Relative Severity Index
Türkiye [145,219]	0.0	0.15	0.9	1.5	Medium-High
Germany [136,210–212,214,216]	0.0	0.15	0.9	1.5	Medium-High
Denmark [223]	0.0	0.15	0.85	1.5	Medium-High
Finland [180]	0.0	0.2	0.85	1.5	Medium-High
Spain [210,221]	0.2	0.5	0.95	1.5	High
Italy [210]	0.2	0.5	0.9	2.0	High
Australia [136,152,211,212]	0.0	0.45	0.8	0.45	Medium
Saudi Arabia [215]	0.0	0.3	0.9	3.0	High
Sweden [136]	0.2	0.25	0.8	1.3	Medium-High

Following fault clearance, facilities are expected to restore active power output in a controlled manner to support voltage and frequency stabilization [225,226]. Grid codes typically define recovery behavior using two parameters: recovery time (T_m) and tolerance (tol). T_m specifies the maximum allowable time for restoring active power close to the pre-fault level, while tol defines the permissible deviation from the pre-fault power P_o. For instance, a tolerance of 0.05 p.u. requires the facility to reach at least 0.95 p.u. of P_o within the defined T_m. For instance, a tolerance of 0.05 p.u. requires the facility to reach at least 0.95 p.u. of P_o within the defined T_m. Accordingly, lower T_m values and narrower tolerance margins correspond to stricter and more technically challenging recovery requirements.

Figure 14 provides a comparative overview of T_m and tolerance values specified in different national grid regulations. The graphical envelopes reflect the officially defined post-fault recovery limits published in the respective grid codes and are presented to ensure accurate representation of regulatory requirements. A pronounced diversity in recovery characteristics is observed across jurisdictions, indicating substantial differences in allowable recovery durations and voltage tolerance thresholds. Australia and the UK impose comparatively stricter recovery conditions, with recovery times as short as 0.1–0.5 s

and tolerance values typically ranging between 0.05 and 0.10 p.u., whereas Türkiye and Germany define intermediate recovery requirements, allowing recovery times of up to approximately 5 s. These variations reflect distinct regulatory strategies in balancing fast dynamic stabilization against equipment stress and operational flexibility. By harmonizing these parameters within a unified comparative structure, the study highlights structural differences in post-fault performance expectations across regulatory frameworks. The comparative representation therefore contributes to understanding how grid codes are progressively redefining active power recovery as a measurable and verifiable dynamic stability requirement.

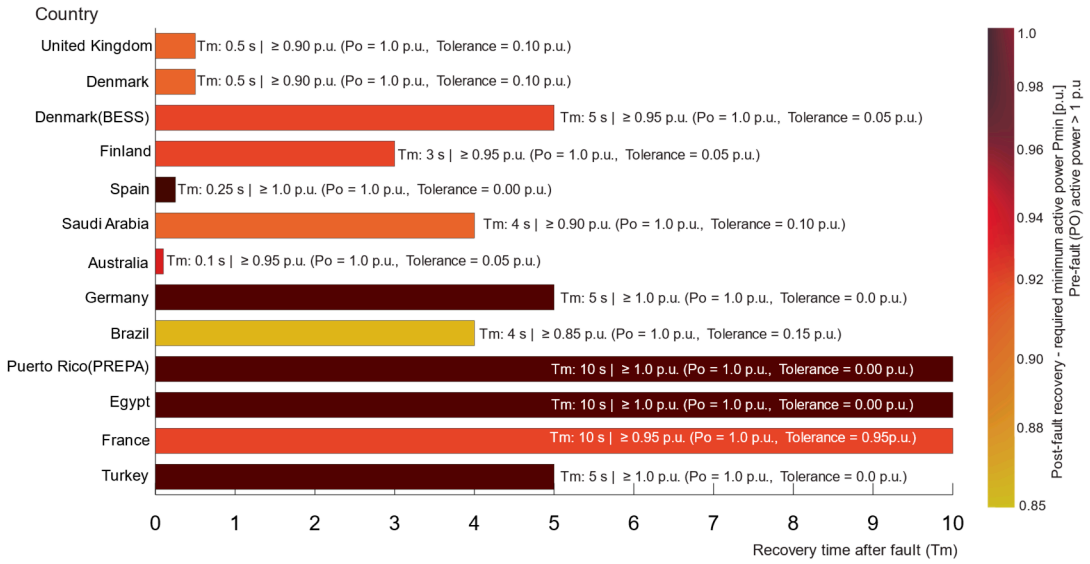

Figure 14. Cross-country comparison of post-fault active power recovery criteria and their impact on dynamic stability requirements. The data presented were compiled from references [152,180,215,219,223].

Reactive current support during faults constitutes another differentiating aspect of LVRT requirements. The K-factor, which defines the slope of reactive current injection as a function of voltage deviation, is not explicitly specified in many grid codes, including the Turkish Grid Regulation. Nevertheless, equivalent requirements are defined by using alternative terminology in several countries. In the Danish Technical Regulation, this requirement is referred to as Fast Fault Current, specifying that a facility must provide 1 p.u. reactive current when voltage decreases from 0.9 to 0.5 p.u., corresponding to a K-factor of 5 [223]. Reported values in the literature include K = 2.5 for Finland [227], 5 for the UK [179], 2 for Saudi Arabia [215], and 2 for Germany [228], highlighting substantial variation in national expectations for reactive current support.

In addition to magnitude, the response time of reactive current injection is a decisive parameter for the dynamic performance of inverter-based generation and storage systems. The Turkish Grid Regulation requires reactive current support to be provided within 60 ms with a tolerance of ±10%. Comparable requirements differ among countries: Denmark specifies a response time of 100 ms with ±20% tolerance, Finland defines 60–80 ms with +20%/−10% tolerance, the UK requires 65% of reactive current within 60 ms and full response within 120 ms, and Saudi Arabia specifies a response time of 60 ms. These differences reflect national grid characteristics, including short-circuit strength, IBR penetration, and system stability requirements.

5.1.2. High-Voltage Ride-Through

HVRT requirements constitute a critical technical criterion that defines the ability of inverter-based generation and energy storage facilities to remain connected to the

grid and contribute to system stability during sudden voltage surges. In grid codes, HVRT performance is typically characterized by two parameters: the overvoltage level (V_p, p.u.) and the maximum allowable duration (T_m, s) for which this voltage can be sustained without disconnecting. Accordingly, HVRT capability represents a standardized performance expectation whereby facilities must tolerate voltage rises up to a specified V_p level for the duration of Tm while maintaining grid connection.

A comparative assessment of HVRT requirements across countries reveals pronounced regional differences in both voltage thresholds and permissible durations. In several European grid codes, including those of Germany, Italy, and Denmark, overvoltage limits are commonly defined in the range of 1.2–1.3 p.u., with allowable durations typically restricted to short intervals between 0.1 and 0.5 s. These requirements emphasize rapid transient tolerance while limiting prolonged exposure to elevated voltage levels. In contrast, Finland adopts a notably more stringent approach, permitting facilities to remain connected for durations of up to 5 s at voltage levels exceeding 1.2 p.u., reflecting a higher tolerance for sustained overvoltage conditions. Figure 15 provides a comparative overview of HVRT difficulty levels among countries by jointly considering the specified overvoltage magnitude and the maximum allowable duration. Higher difficulty scores correspond to combinations of elevated V_p values and extended T_m durations, indicating more demanding technical requirements for inverter-based generation and storage systems. By integrating magnitude and duration parameters into a unified comparative structure, the study enables systematic cross-country evaluation of overvoltage tolerance characteristics rather than merely presenting isolated regulatory limits. The observed diversity in HVRT criteria highlights how national grid codes balance equipment protection, system stability, and operational robustness in response to differences in network characteristics and IBR penetration.

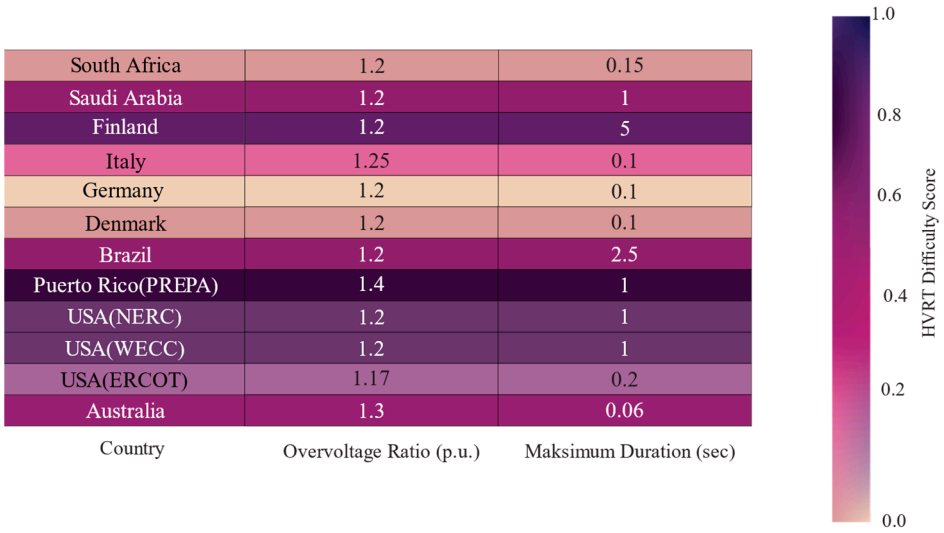

Figure 15. Comparative HVRT performance expectations and their role in shaping overvoltage tolerance strategies. The data presented were compiled from references [136,151,152,180,209–212,215,224,229].

5.2. Reactive Power Support and Voltage Control

Across different countries, reactive power capability and voltage control requirements for WPP, SPP, and ESS are defined within a broadly similar technical framework; however, notable differences arise in detailed parameterization and performance expectations. A comparative assessment of national grid codes reveals that while general principles, such as mandatory reactive power provision and voltage regulation at the point of connection, are widely shared, significant variations exist in key technical parameters. These include reactive power capacity limits, reserve margins, voltage-reactive power slope definitions,

deadband settings, and dynamic response times. Such differences are closely linked to country-specific grid characteristics, including short-circuit strength, network topology, renewable energy penetration levels, and operational security criteria.

In this context, Figure 16 provides a comparative overview of the reactive power capacity requirements defined for RES and ESS in different countries; Table 4 summarizes the reactive power performance criteria specified for ESS. These analyses demonstrate that reactive power support in modern power systems is not only a grid code requirement but also a strategic necessity for high-penetration renewable integration. The comparative synthesis therefore highlights how national frameworks are progressively formalizing reactive power obligations to maintain voltage stability, network robustness, and operational flexibility under increasing RES and ESS penetration.

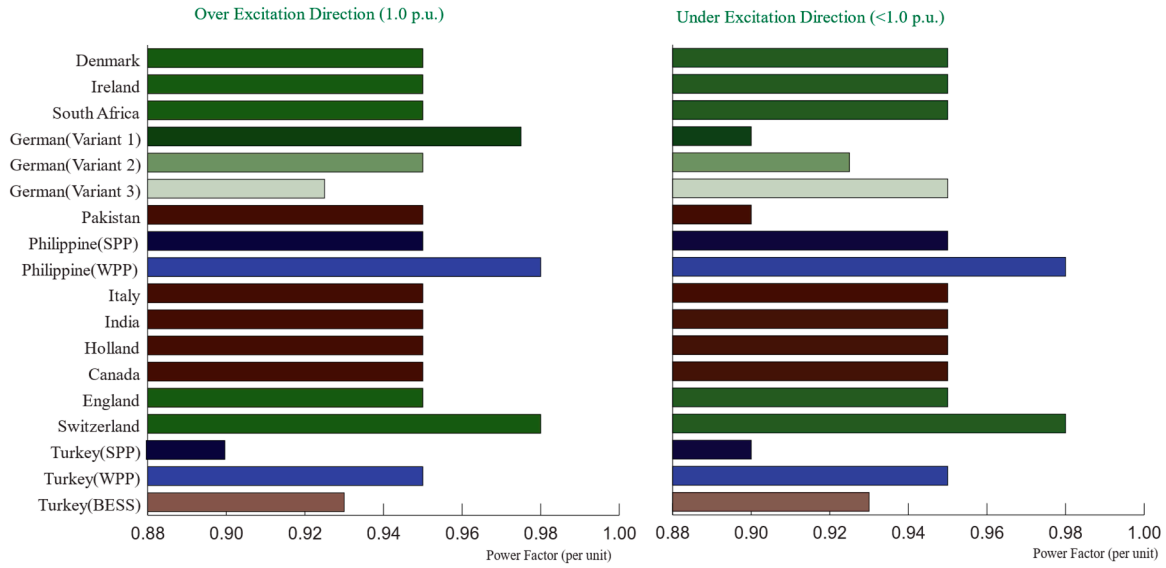

Figure 16. Reactive power capability requirements across countries and their contribution to voltage regulation evolution. The data presented were compiled from references [145,210,212,219,221,223,224,230–239].

Table 4. Reactive power and voltage control requirements for ESS in different countries.

Country	Reactive Power Capacity	Power Factor	Droop Settings	Reactive Power Response	Tolerance/Deviation
UK [229,240,241]	20–50% of nominal capacity	0.95	NA	0.2 s from voltage change; 1 s to 90% level	In steady state, reactive power exchange is close to zero; tolerance ± 5% of nominal active power
Denmark [242]	±0.33 p.u	0.95	2–7%, margin of error ± 3%; deadband ± 5%, step size 0.5%	90% of the set value in 1 s, 100% in 5 s	Deadband ± 5%
Finland [180]	±0.33 p.u	0.95	2–7%, step ≤ 0.5%	0–90% change in 0.2–1 s; reaches target within 5 s	In steady state ± 5% (maximum ± 1 Mvar); overshoot ≤ 15%
Türkiye [135]	≥40% reactive power reserve (active power > 10%)	NA	2–7%	Starts response within 200 ms; 90% target 1 s; equilibrium 2 s ± 2%	NA

NA: not available.

Voltage operating range requirements further differentiate national grid codes. These requirements define the minimum and maximum voltage limits within which generation and storage facilities must remain connected and operational [243]. Grid operators specify

these limits to ensure system stability and to protect network components against both transient and sustained voltage deviations. Figure 17 compares the voltage operating ranges and mandatory withstand durations defined in different countries, indicating the minimum time periods during which facilities must continue operation following deviations from the nominal 1 p.u. voltage level at the connection point. The observed variations underline the diversity of national approaches to voltage robustness and provide a structured basis for assessing the voltage withstand performance of inverter-based generation and storage systems on an international scale.

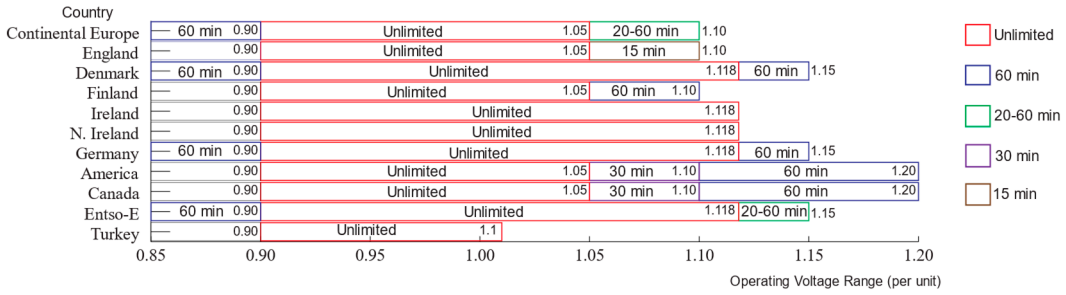

Figure 17. The minimum continuous operation periods and their implications for system resilience under disturbance conditions. The data presented were compiled from references [145,152,170,180,212,219,244–247].

5.3. Active Power Support and Frequency Control

Active power-frequency control constitutes a fundamental functional requirement for inverter-based generation units and ESSs, as it directly affects system frequency stability. Accordingly, grid codes in many countries define detailed technical requirements for frequency-responsive active power control. Figure 18 presents a comparative overview of the threshold values associated with the LFSM-U, LFSM-O, and FSM operating modes applied in different countries for RESs. While the general operating principles of these modes are largely aligned across regions, notable differences are observed in technical parameters such as tripping frequency limits, droop slopes, response sensitivity, and tolerance ranges. These variations reflect regulatory approaches shaped by national system inertia levels, short-circuit strength, renewable energy penetration, and operational reliability objectives.

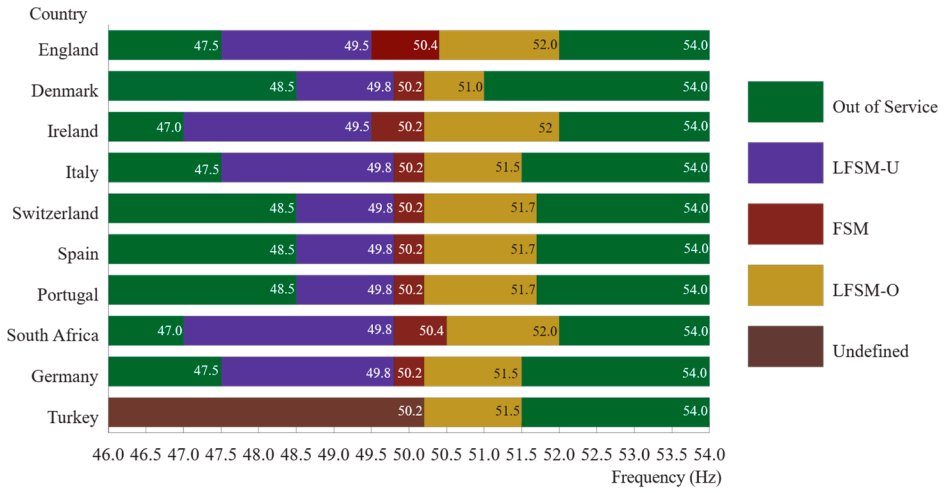

Figure 18. Frequency control activation thresholds (LFSM-U, LFSM-O, FSM) and their influence on frequency response standardization. The data presented were compiled from references [127,136,145,152,173,219,223,230,239,243,248].

Within this broader context, similar structural trends can be observed in the Turkish transmission system. The increasing penetration of inverter-based renewable generation

has progressively reduced the relative contribution of synchronous generation during certain operating periods, particularly under low-load and high-RES conditions. Publicly available TEİAŞ system reports indicate that such operating scenarios may lead to lower effective inertia margins and reduced short-circuit strength at specific transmission nodes [135]. Under these conditions, system frequency containment and voltage stability become more sensitive to inverter tripping behavior and insufficient dynamic support functions, thereby reinforcing the importance of clearly defined HVRT and frequency response requirements in the Turkish grid code.

Limited LFSM-U provisions in Türkiye for RES may create operational vulnerabilities during underfrequency events. Without clearly defined activation thresholds and response parameters, inverter-based generation may not provide sufficient active power increase during frequency drops. LFSM-U requirements have recently been introduced for ESSs in Türkiye; however, strengthening the LFSM-U framework would enhance the utilization of RES as frequency support resources and improve overall system resilience.

Table 5 provides a comparative overview of frequency regulation requirements specified in national and regional grid codes based on key technical parameters, including frequency deadband settings, droop characteristics, response times, minimum active power contributions, and required operating durations under frequency deviations. The deadband and droop parameters primarily correspond to FSM operation, which is mandatory for ESSs in the Turkish grid code, while not required for RPPs. Response time requirements are not explicitly defined for renewable generation units in Türkiye and are traditionally associated with synchronous generators.

Table 5. Comparative analysis of frequency regulation requirements in grid codes across different regions.

Region/Country	Deadband Adjustment (Hz)	Permitted Setting Range (Hz)	Droop	Response Time Requirements (s)	Minimum Active Power Output (%)	Operating Duration (s)
Global—IEEE 1547-2018 [123]	0.036	0.017–1.0	%5 (3–5%)	5 s (0.2–10 s)	20	NA
UK [179,249,250]	0.015	NA	3–5%	10	10	30
Denmark [246]	≤0.010	NA	2–12%	15 and 30 (depending on the model)	10	NA
Finland [180,251]	0.010	0–0.1	%4 (2–12%)	50% response 5 s, 100% response 30 s	10	120
Ireland [230]	≤0.015	±0.015	3–15%	2–10	5	30
Italy [236]	0.010–0.020	±0.010–±0.020	2–5%	15–30	NA	900
ENTSO-E [151]	0.01	0–0.5 (±0.05)	2–12%	2–30	10	NA
Türkiye [145]	0.01	0–0.2	2–7%	15–30	10	1800

NA: not available.

The operating duration values indicate the minimum time during which units are required to remain connected and actively support the system when frequency deviates beyond normal operating limits, revealing notable differences in regulatory implementation despite a common objective of maintaining frequency stability.

In addition to dynamic frequency response characteristics, frequency operating range requirements define the limits within which generation and storage facilities must remain connected and operational. These limits are established by grid operators to ensure both operational safety and system integrity under frequency deviations. For instance, ENTSO-E requires generation facilities to remain in continuous operation within the 49.0–51.0 Hz frequency range [236,252].

Similarly, the Turkish Electricity Grid Regulation requires WPPs to maintain continuous operation within defined frequency operating limits, thereby supporting system frequency stability during normal and disturbed operating conditions [253]. Figure 19 compares the frequency operating ranges specified in different countries, highlighting both common practices and region-specific deviations in frequency withstand requirements.

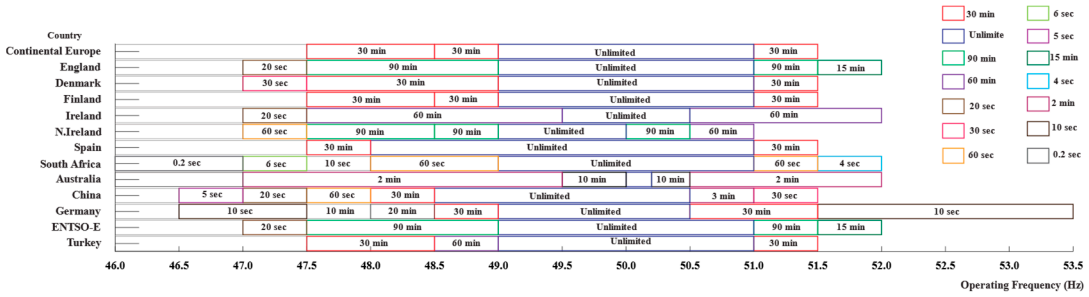

Figure 19. National frequency operating ranges and their relevance to low-inertia system adaptation. The data presented were compiled from references [145,180,210,216,219,221,230,232,244,246,248,254–261].

6. Key Challenges and Recommendations for the Turkish Grid Code

6.1. Defining HVRT Boundaries

When examining various regional grid regulations, it is observed that HVRT limits are mostly defined in the range of 1.2–1.3 p.u. and withstand durations vary between 0.1 and 0.5 s in different regions such as ENTSO-E countries, America, Australia, Saudi Arabia, and South Africa. The gradual definition of HVRT requirements in these regions based on voltage level reflects a common approach aimed at enabling inverter-based generation and storage facilities to contribute to the grid under overvoltage conditions.

The current Turkish Grid Regulation does not define any technical limits for HVRT; the regulation only requires that the nominal operating voltage be within the range of 0.9–1.1 p.u. Therefore, there is no regulation regarding how long facilities must remain connected to the grid at voltages above 1.1 p.u. Addressing this technical gap is important, particularly in terms of increasing the resilience of inverter-based generation and energy storage facilities against overvoltage conditions. To this end, it is recommended that HVRT requirements for Türkiye be defined using a phased approach. The proposal presented in this study is structured based on the Voltage–Time curve shown in Figure 20. In this context:

- As long as the PCC voltage remains within the boundaries of Zone A, IBRs are expected to remain connected to the grid and continue to provide voltage support.
- It is recommended that facilities remain operational for at least 1200 s (20 min) at the 1.15 p.u. level.
- When the voltage reaches 1.25 p.u., the facilities must maintain their connection for at least 60 s.
- If the voltage exceeds 1.30 p.u., facilities are required to remain connected to the grid for at least 0.1 s.

The absence of explicitly defined HVRT voltage–time withstand characteristics in the current Turkish Electricity Grid Regulation may introduce stability risks under high inverter-based resource penetration. In scenarios with large-scale PV, WPP, and ESS integration, temporary overvoltage events exceeding 1.1 p.u. may trigger coordinated inverter disconnections if no mandatory HVRT envelope is defined. Such simultaneous tripping behavior can reduce available reactive power support, weaken voltage regulation capability at the point of common coupling, and amplify voltage oscillations in grid.

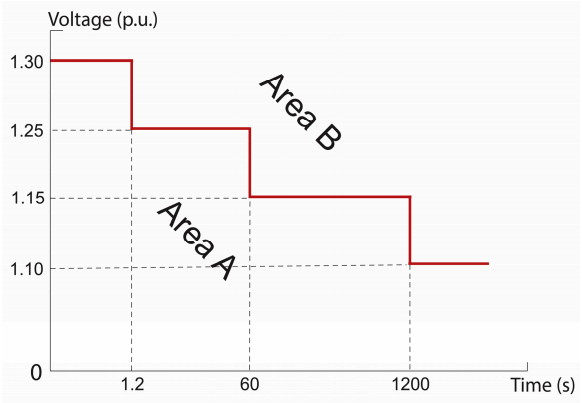

Figure 20. Proposed HVRT voltage–time characteristic to enhance overvoltage resilience in the Turkish grid code.

6.2. Determination of the K-Factor Within the Scope of FRT

The slope of the reactive current support that must be provided by inverter-based generation and storage facilities under fault conditions is expressed by a coefficient defined as the K-factor in the grid regulations of many countries [262]. The K-factor determines the relationship between voltage drop and reactive current increase, directly affecting the dynamic characteristics of voltage support during faults [263]. An examination of international practices reveals that the K-factor is defined as 2 in Saudi Arabia [215], 2.5 (in the range of 2–6) in Finland [227], and 2 (in the range of 2–10) in Germany [228]. The Danish Technical Regulation states that if the voltage drops from 0.9 p.u. to 0.5 p.u., the facility must be able to supply 1 p.u. of reactive current with a 20% tolerance, indicating that the K-factor for Denmark is 5. It has been reported that a similar value of 5 is adopted in the UK [179]. This distribution reveals that expectations regarding reactive current support during faults vary significantly between countries.

The Turkish Electricity Grid Regulation does not contain any definition of the K-factor. This situation creates a gap in terms of standardizing the reactive current support to be provided during outages and indicates the need to define a K-factor range that is consistent with international regulations.

Not only the slope but also the rate at which reactive current support is provided is critical for the dynamic performance of inverter-based generation and storage systems. The Turkish Grid Code requires reactive current support to be provided within 60 ms. In other countries, the specified response times and associated implementation criteria differ. In other countries, the time and tolerance values differ: in Denmark, it must be provided within 100 ms with a tolerance of 20%; in Finland, within 60–80 ms with a tolerance of +20%/−10%; in the UK, 60 ms for 65% of the reactive current and 120 ms for the entire reactive current; and in Saudi Arabia, it must be provided within 60 ms. These differences stem from variations in countries' priorities regarding grid stability, short-circuit levels, grid topologies, and the maturity levels of inverter-based technologies.

The slope of the reactive current support is commonly calculated in the literature using the ratio in (1) [264]. When examining (2) and (3), the K factor is calculated as 2.5 and 5.

$$\mathrm{K} = \frac{\Delta I_q}{\Delta V} \tag{1}$$

$$\mathrm{K} = \frac{1-0}{0.9-0.5} = 2.5 \tag{2}$$

$$\mathrm{K} = \frac{1-0}{0.9-0.7} = 5 \tag{3}$$

In this context, the reduction in the voltage change range requires the definition of a higher K-factor value for the same reactive current increase. In other words, as the K-factor increases, the reactive current support provided by the inverter during a fault exhibits a faster and more aggressive character [265]. This situation offers a critical advantage, particularly for maintaining grid stability at low voltage levels. When international practices and technical calculations are evaluated together, it is anticipated that defining a K-factor in the range of 2.5 to 5 would be appropriate for the Turkish Electricity Grid Regulation. This range corresponds to the values used in advanced grid systems such as Finland [227] and Germany [228], and provides optimal control performance in terms of ensuring effective voltage support in different fault scenarios [265].

Figure 21 illustrates voltage-reactive current characteristics corresponding to different K-factor values. Based on these characteristics, it is recommended that the transmission system operator defines appropriate K-factor settings in a similar manner to ensure consistent reactive current response under voltage disturbances.

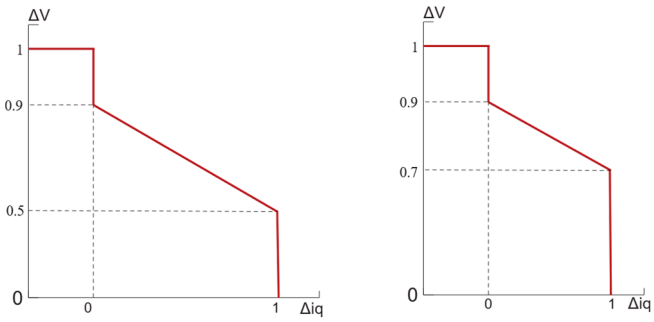

Figure 21. Proposed K-factor parameterization to strengthen reactive current support performance in Türkiye.

6.3. Expansion of the Frequency Operating Range and the Definition of LFSM-U for RES

The Turkish Electricity Grid Regulation defines the frequency operating range as 47.5–51.5 Hz, which corresponds to a total operating band of 4 Hz [145]. This wide range contributes to system stability by allowing generation units, especially in low-inertia power systems, to remain connected to the grid for longer periods during faults, fluctuations, or transient oscillations [266]. Given the increasing penetration of RESs in Türkiye, frequency stability requirements may need to be reassessed through a more clearly parameterized and, where justified, expanded operating framework [267].

In this regard, the new frequency operating range proposal presented in Figure 22 has been developed based on both international practices. The proposed approach aims to enhance the stability performance of inverter-based generation and storage facilities during faults and improve post-fault recovery behavior. This will enable the frequency flexibility requirements arising from increased renewable energy penetration to be met more effectively.

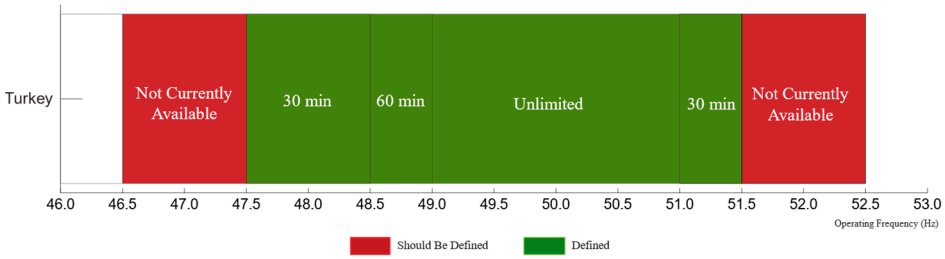

Figure 22. Proposed expansion of frequency operating ranges to improve flexibility and stability margins in Türkiye.

The current LFSM-U framework for RES in Türkiye is relatively limited and may lead to operational risks during underfrequency conditions. In the absence of well-defined activation criteria and response characteristics, inverter-based resources may fail to deliver adequate active power support when frequency declines. Although LFSM-U requirements have recently been introduced for ESS in Türkiye, further strengthening and clarifying these provisions would enable better use of RES for frequency support and contribute to greater system stability and resilience.

6.4. Defining the Initial Response Time in Active Power Control

The initial response time is a fundamental performance criterion that defines the moment when the facility begins to actively change power following a frequency deviation or operator command [268]. An examination of national and international grid regulations reveals that different practices are adopted regarding this time. For example, while the initial response time is set at 1 s in Australia [269], the UK defines this value as 0.5 s [229]. In contrast, the Turkish Electricity Grid Regulation [145] regulates redispatch-up and redispatch-down rates, while no explicit criterion is provided regarding the initiation of active power response. This situation creates a gap in terms of the consistency and predictability of the responses of IBRs and ESSs to frequency events. Therefore, as shown in the example in Figure 23, it is important to clearly define the time interval during which the facility should begin active power changes from the moment the frequency deviation occurs or an active power setpoint sent. Adding a clear value for the initial response time in the range of 0.5–1 s to the ESS will increase the effectiveness of inverter-based generation units and ESSs in frequency control; it will also provide a more precise framework for the system operator's expectations regarding frequency stability.

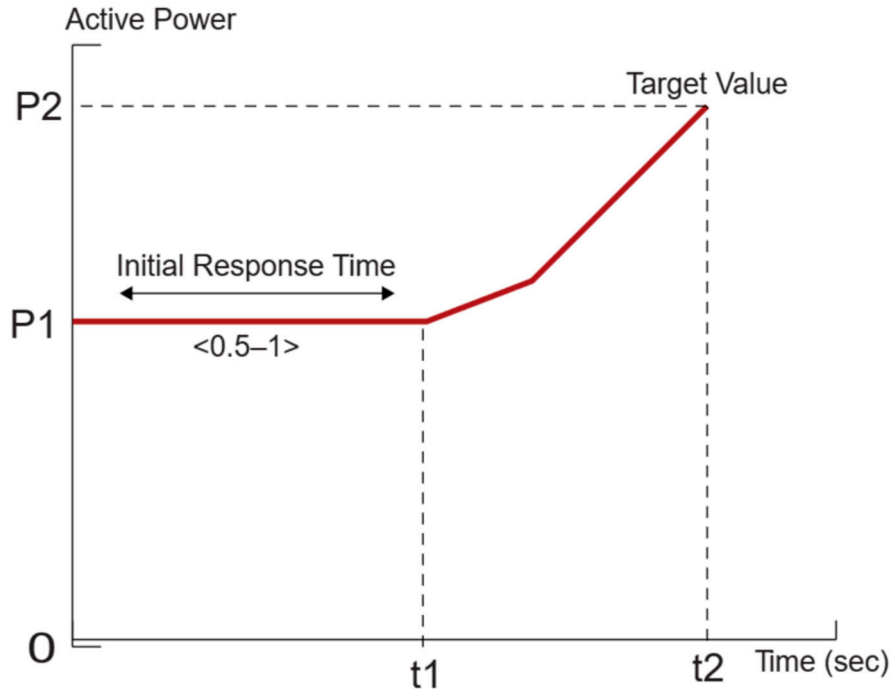

Figure 23. Standardization of initial response time definitions for improved dynamic compliance assessment.

6.5. Extension of Voltage Limits

In ENTSO-E member countries, the voltage range within which generation facilities can remain in continuous operation is generally defined as 0.85–1.118 p.u., and this approach allows power plants to operate with a wider tolerance against temporary voltage

deviations [151]. In contrast, the Turkish Electricity Grid Regulation defines a narrower voltage band, setting 0.9–1.1 p.u. as the operating condition. Controlled expansion of this band under specific conditions and for short periods can prevent inverter-based generation and ESSs from tripping unnecessarily during temporary voltage deviations. The extension of voltage limits is shown in Figure 24.

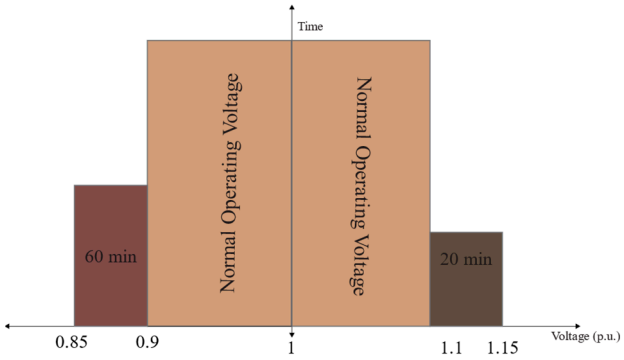

Figure 24. Proposed extension of voltage limits to support enhanced operational robustness under high IBR penetration.

6.6. Redefining Requirements for Hybrid Power Plant

Although the Turkish Electricity Network Regulation defines the basic technical requirements for HPPs, the comparative analysis presented in Table 6 shows that the current regulations need to be expanded in terms of alignment with international practices. In this context, defining the reactive current support required from HPPs during FRT based on total installed capacity rather than just licensed capacity will strengthen the voltage support provided to the grid during faults and contribute to reducing fault depth. Similarly, addressing reactive power reserve obligations based on installed capacity will enable HPPs to contribute more effectively to voltage stability under normal operating conditions.

6.7. Completion of Rapid Frequency Control

The fact that the FFR function has not yet been defined in the Turkish Electricity Grid Regulation creates a significant gap in terms of ensuring frequency stability in low-inertia power systems. Particularly in sudden deviation conditions where the frequency can drop below 49.5 Hz in a very short time, the ability of inverter-based generation and storage facilities to provide rapid and additional frequency support is critical in limiting frequency deviation and maintaining stability across the system. The fact that comprehensive technical requirements for FFR are clearly defined in ENTSO-E countries and Australia demonstrates the need for similar regulations in Türkiye [206].

In this context, limiting the FFR time to a maximum of 1 s and defining the active power contribution to be provided within the range of 5–10% of the plant's nominal power is considered an appropriate practice. Furthermore, clearly defining the tolerances (e.g., $\pm 1\%$) regarding the accuracy of the FFR support provided and standardizing the test procedures for verifying this performance by adding them to the Electricity Grid Regulation will both increase transparency in the audit processes and significantly strengthen system reliability.

6.8. Identification of Synthetic Inertia Requirements

In regions such as ENTSO-E countries and Canada inverter-based generation units are expected to provide resynthesis inertia, and this function is generally mandated through the dP/df parameter, which defines the relationship between the rate of power change and the rate of frequency change [270]. However, the Turkish Electricity Grid Regulation does

not impose any requirement for a synthetic inertia function. However, as the share of RES in the system increases, grid inertia decreases, leading to higher RoCoF values [24].

Table 6. Summary of requirements specified in grid regulations by source type.

Requirement	Hybrid (WPP + SPP + ESS)	WPP	SPP	ESS
Operating Limits (Voltage, Frequency, RoCoF)	Similar	Similar	Similar	Similar
FRT	Reactive current support during a fault can be requested based on installed capacity, not licensed capacity.	Similar	Similar	Similar
Frequency Control	In addition to reducing generation during frequency increases, the ESS may be required to engage in traction	Similar	Similar	Similar
Active Power Control	Similar	Similar	Similar	Similar
Reactive Power Reserve	Reactive power reserve may be requested based on installed capacity instead of licensed capacity. Additionally, asynchronous reactive power service may be provided in AS	Similar	Similar	Asynchronous reactive power service can be provided in AS
POD	Similar	Similar	Similar	Similar
Synthetic Inertia	Similar. However, it can provide higher support depending on the license power	Similar	Similar	Similar
Fast Frequency Response	Similar. However, it can hold a larger reserve	Similar	Similar	Similar
Black Start	Grid forming technology for ESSs is required	Nothing	Nothing	Grid forming technology for ESSs is required

NA: not available.

Synthetic inertia support emerges as a critical mechanism that directly contributes to maintaining frequency stability by limiting RoCoF values.

Upon reviewing current international network regulations, it is recommended that the following points be added to the Turkish Electricity Grid Regulation:

- Determination of the synthetic inertia function for inverter-based facilities connected to the transmission system with a capacity of 30 MW and above;
- Indicative response time targets in the order of several milliseconds (5–10 ms), recognizing that actual achievable performance depends on measurement delays, control dynamics, plant-level communication latency, and aggregation models;
- An adjustable inertia constant within a reference range (3–5 s), to be optimized based on system inertia requirements and stability studies.

The implementation of these regulations will significantly contribute to maintaining system inertia, limiting RoCoF values, and thus sustainably strengthening frequency stability in the Turkish electricity system, even if the proportion of inverter-based generation increases.

6.9. Identification of Power Oscillation Damping Requirements

In large interconnected systems (e.g., Scandinavia, Spain, and Germany), inverter-based generation facilities are expected to provide a POD function capable of suppressing power oscillations within a specific frequency range [271]. This application increases system stability and prevents the propagation of oscillations in interconnected regions. In this

context, a similar approach is adopted in the Turkish Electricity Grid Regulation, and the following regulations are recommended:

- The presence of a POD function in inverter-based generation facilities connected to the transmission system with a capacity of 30 MW or more;
- Defining the effective range of POD controllers as 0.1–2 Hz;
- Designing the function to operate continuously under normal operating conditions;
- Documentation of POD performance through model validation and field testing.

For the analysis and verification of the POD function, a test approach like the Swedish Svenska kraftnät [197] application can be adopted. The tests that can be applied in this context are as follows:

1. Simulation test: The improvement in the damping ratio of the POD should be evaluated by creating oscillations in the 0.1–2 Hz range on a standard system model defined by TEİAŞ.
2. Open-loop frequency response test: Reactive power-voltage response should be measured by applying small-amplitude sinusoidal signals to the central voltage reference; phase shift is expected to be between $\pm 30^{\circ}$ in the 0.1–2 Hz range. Additionally, the active power response should be measured, and a phase shift of 150–210° is required in the 0.1–2 Hz range.

The implementation of these tests will demonstrate that POD controllers increase stability without creating adverse interactions under real system conditions and will enable verification of the contribution of inverter-based generation facilities to system dynamics. Consequently, the proposed regulations will make significant contributions to maintaining system stability in the Turkish electricity system alongside increasing inverter-based generation rates.

6.10. Reactive Power Support for Distribution Connected Power Plant

If renewable energy generation facilities connected to the distribution system do not contribute to reactive power support, it is estimated that unavoidable voltage problems will occur in the distribution system. To prevent this situation and ensure that the system voltage is kept within operating limits, considering the requirements of different countries [151,180,223,241], the following technical principles are recommended for Türkiye:

- Unlicensed power plants with an installed capacity of less than 10 MW must provide reactive power support with a fixed power factor determined by the Electricity Distribution Company.
- Unlicensed power plants with an installed capacity of 10 MW and greater than 10 MW must have a reactive reserve at a power factor level of ± 0.95 and be able to respond dynamically to voltage control. The reactive power response to voltage changes at the connection point must start within 0.2 s at the latest, reach 90% within 1 s, and reach a stable state within 2 s with a tolerance of 5%.

6.11. Identification of Phase Jump Tolerance Requirements for Grid-Forming Inverters

With the increasing penetration of IBRs, power systems are exposed to rapid voltage phase angle variations during grid disturbances such as faults, switching events, generator tripping, and fault clearing [272]. Recent disturbance analyses show that sudden phase angle jumps, particularly in weak grids, may lead to inverter misoperation, loss of synchronism, or unintended tripping due to control and protection interactions rather than fundamental voltage or frequency limit violations [273]. Unlike synchronous generators, IBRs rely on fast control loops and synchronization mechanisms, making them particu-

larly sensitive to abrupt phase angle changes [274]. EMT studies further demonstrate that voltage phase angle jumps in the upstream grid can be amplified at inverter terminals depending on grid strength and operating point, potentially triggering PLL instability, overcurrent, or overvoltage protection even during non-severe disturbances [272].

Recognizing this issue, NERC explicitly addressed phase jump ride-through capability in the PRC-029-1 (Frequency and Voltage Ride-through Requirements for Inverter-based Resources, NERC, Atlanta, GA, USA, 2025) Reliability Standard, emphasizing that voltage phase angle jumps are common occurrences on the bulk power system and should not result in unnecessary inverter tripping [275]. Accordingly, PRC-029-1 defines a minimum phase jump ride-through capability of 25 electrical degrees, which is widely regarded as a practical and representative threshold for IBRs connected to the transmission system.

In the Turkish context, recent draft regulations for grid-forming inverter technologies acknowledge the importance of phase angle disturbances and require grid-forming inverter-based facilities to remain connected during sudden voltage phase angle changes of up to 60 electrical degrees, while providing active power support within equipment limits. While advanced grid-forming inverter designs may tolerate such large phase angle deviations, defining a clear minimum requirement remains essential to ensure consistent and predictable ride-through behavior across inverter-based facilities [145]. Accordingly, based on international practice and system reliability considerations, it is recommended that the Turkish Electricity Grid Regulation specify a minimum phase jump ride-through requirement in the range of 20–30 electrical degrees for transmission-connected grid-forming inverter-based facilities, while allowing higher tolerance levels to be demonstrated through validated EMT studies.

Section 6 has examined the Turkish Electricity Grid Regulation from multiple technical dimensions, including FRT performance, reactive and active power control mechanisms, frequency stability provisions, modeling and compliance assessment frameworks, and future-oriented enhancement strategies. To provide a consolidated and structured overview of these analyses, Table 7 presents a comparative synthesis of the current Turkish provisions, the enhancement proposals developed in this study, and representative international practices discussed throughout the chapter.

Table 7. Comparison of current Turkish grid code provisions proposed technical enhancements, and international practices.

Technical Domain	Current Turkish Grid Code	Proposed Enhancement	International Practice
HVRT—Overvoltage Magnitude & Duration	NA HVRT technical limits defined; only nominal 0.9–1.1 p.u. range specified	1.15 p.u. $\geq$ 1200 s; 1.25 p.u. $\geq$ 60 s; 1.30 p.u. $\geq$ 0.1 s	0.1–0.5 s (ENTSO-E [151], Australia [269], Saudi Arabia [215], South Africa [232])
Reactive Current Support—Response Time	Reactive current must be provided within 60 ms can be requested based on installed capacity, not licensed capacity	Maintain 60 ms with standardized tolerance definition	Finland: 60–80 ms (+20%/−10%) [227]; UK: 60 ms (65%), 120 ms (100%) [179]; Saudi Arabia: 60 ms [215]
Frequency Operating Range	47.5–48.5 Hz (30 min); 48.5–49.0 Hz (60 min); 49.0–51.0 Hz (Unlimited); 51.0–51.5 Hz (30 min)	46.5–47.5 Hz/>51.5–52.5 Hz: To be defined	Frequency operating ranges defined with structured performance expectations (Figure 19)
Active Power Response—Initial Response Time	No explicit definition: redispatch-up/down rates defined only	Define initial response time in the range of 0.5–1 s	Australia: 1 s [269]; UK: 0.5 s [229]
Voltage Operating Band (Continuous Operation Limits)	0.9–1.1 p.u.	0.85–1.15 p.u.	0.85–1.118 p.u. continuous operating range in ENTSO-E member countries [151], as discussed and illustrated in Figure 17

NA: not available.

7. Conclusions

This study has provided a comprehensive comparative analysis of grid code requirements applicable to inverter-based RPPs and ESSs, with particular focus on the Turkish Electricity Grid Regulation. Using a harmonized and parameter-based framework, this study enabled systematic comparison of FRT capability, reactive current support, active and reactive power control, frequency response functions, advanced grid support functionalities, and compliance verification practices across multiple jurisdictions. The comparative assessment indicates several areas where the current Turkish framework could be further developed in line with evolving international practices. These include the progressive definition of HVRT voltage–time withstand characteristics, FFR parameters, the structured incorporation of synthetic inertia and POD capabilities within the regulatory architecture. Furthermore, for ESS-integrated HPPs, the study highlights the opportunity to reassess reactive power capability limits from a system-level perspective, particularly under increasing inverter-based penetration. In parallel, under high renewable integration scenarios where short-circuit strength may decrease, the process f reviewing and potentially expanding voltage operating boundaries emerges as a constructive step toward reinforcing voltage stability and overall system robustness.

From a broader international perspective, the findings reflect a global transition toward performance-based and continuously monitored grid code architectures designed to address low-inertia system dynamics. As inverter-based generation and ESSs progressively replace synchronous resources, regulatory frameworks increasingly evolve toward structured frequency support definitions, enhanced voltage withstand characteristics, oscillation damping provisions, and continuous grid code compliance monitoring mechanisms beyond one-time commissioning tests. In this context, the analytical framework developed in this study not only supports forward-looking and adaptive grid code evolution in Türkiye but also provides a transferable reference for other power systems integrating high shares of inverter-based generation and storage, where adaptive voltage margins, frequency containment capability, and sustained compliance monitoring contribute to long-term system stability.

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Abbreviations

The following abbreviations are used in this manuscript:

PV	Photovoltaic
BESS	Battery Energy Storage System
ESS	Energy Storage System
CSR	Codes, Standards and Regulations
IEC	International Electrotechnical Commission
RES	Renewable Energy Source
PFC	Primary Frequency Control
DG	Distributed Generation
LV	Low Voltage
HESS	Hybrid Energy Storage System
AS	Ancillary Services
ENTSO-E	European Network of Transmission System Operators
FERC	Federal Energy Regulatory Commission
FCR	Frequency Containment Reserve
FRR	Frequency Restoration Reserve
aFRR	Automatic Frequency Restoration Reserve
mFRR	Manuel Frequency Restoration Reserve
MV	Medium Voltage
VSG	Virtual Synchronous Generator
UK	National Grid
FFR	Fast Frequency Response
ANM	Active Network Management
TEİAŞ	Türkiye Electricity Transmission Inc.
SOC	State of Charge
MG	Microgrid
ADN	Active Distribution Network
PSO	Particle Swarm Optimization
SWOT	Strengths, Weaknesses, Opportunities, Threats
DR	Demand Response
LFC	Load Frequency Control
MPC	Model Predictive Control
FRT	Fault Ride Through
GFM	Grid Forming
GFL	Grid Following
RoCoF	Rate of Change in Frequency
PFR	Primary Frequency Response
MILP	Mixed Integer Linear Programming
A-R-OPF	Active-Reactive Optimal Power Flow
PCS	Power Conversion System
EPDK	Energy Market Regulatory Authority
IBR	Inverter-Based Resources
LVRT	Low-Voltage Ride-Through
HVRT	High-Voltage Ride-Through
PCC	Point of Common Coupling
AVR	Automatic Voltage Regulator
SVC	Static Var Compensator
LFSM-U	Limited Frequency Sensitive Mode-Underlimited
LFSM-O	Limited Frequency Sensitive Mode-Overlimited

SPP	Solar Power Plant
WPP	Wind Power Plant
FFC	Fast Fault Current
POD	Power Oscillation Damping
PLL	Phase Locking Loop
POD-P	Active Power Modulation
POD-Q	Reactive Power Modulation
PPM	Power Park Module
AVC	Automatic Voltage Control
VRE	Variable Renewable Energy
RPP	Renewable Power Plant
WTG	Wind Turbine Generator
WECS	Wind Energy Conversion System
WECC	Western Electricity Coordinating Council
MPPC	Master Power Plant Controller

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