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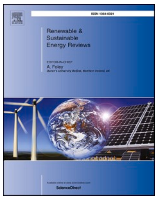

Review of recent developments in grid codes: Focus on compliance testing and grid-forming inverter-based resources

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ABSTRACT

As inverter-based resources (IBRs) integration and cross-border electricity trade grow, harmonized grid codes become critical. Large-scale deployment of IBRs requires standardized, well-defined compliance verification requirements and testing procedures. Moreover, the effective integration of grid-forming (GFM) IBRs in low-inertia power systems needs clear grid code specifications and robust verification frameworks. Therefore, this paper presents a comprehensive review of grid code requirements regarding GFM IBR integration and grid code compliance testing. It offers an in-depth literature review of current methodologies for grid code compliance verification, with a particular emphasis on those recommended by European regulatory frameworks. The paper examines grid code specifications for key GFM functionalities, including voltage-source behavior, inertia emulation, fast fault-current injection, sink for harmonics, sink for unbalance and oscillation damping. Additionally, it discusses various simulation-based test frameworks to verify compliance with core grid-forming capabilities. The primary focus is on European grid codes; however various national and international grid code requirements are also discussed in detail for comparison. This review serves as a foundation for innovation and policy development, supporting system operators, manufacturers, and researchers in deepening their understanding of current regulations and emerging trends.

1. Introduction

The global transition from synchronous generators (SGs) to renewable and inverter-based resources (IBRs) presents several challenges related to power system stability and reliability [1]. Based on their control strategies, IBRs can operate either in grid-following (GFL) mode, where they synchronize to the existing grid voltage and frequency, or in grid-forming (GFM) mode, where they can establish voltage and frequency references. Secure and stable IBR integration continues to be a key concern for power system operators. This integration is governed by grid connection codes, which define the minimum technical, operational, and performance requirements that all power-generating units must satisfy prior to grid connection. Grid codes exist at national, regional, and international levels and play a vital role in shaping energy policies.

European Network of Transmission System Operators for Electricity (ENTSO-E) defines compliance testing as a structured verification process to ensure compliance with the requirements outlined in the grid codes. Under the European regulatory framework, Network Code on Requirements for Generators (NC RfG 1.0), grid code compliance is mandatory for all power generating modules (PGMs, i.e., synchronous generator and IBRs) wishing to connect to the grid. The grid code testing frameworks are as essential as the grid code regulations themselves. Compliance verification is essential for both GFM and GFL technologies. Therefore, the large-scale integration of these technologies demands standardized and harmonized guidelines and procedures for compliance testing, model validation, and certification.

Furthermore, IBRs are undergoing a transition from “being part of grid stability problem” in their grid-following (GFL) role to becoming “part of the solution” through GFM capabilities. Central to this transformation is the deployment of grid-forming (GFM) technology, which can enhance grid stability and resilience by providing ancillary services such as inertia emulation, frequency regulation, voltage support, and black-start [2]. However, the effective integration of GFM IBRs requires standardized functional specifications and interconnection requirements to ensure reliable and secure operation across diverse grid conditions.

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1.1. Literature review

In recent years, several studies have reviewed grid codes, primarily focusing on technical requirements such as low voltage ride-through (LVRT), frequency regulation, and voltage control [3–5]. Very few studies discussed grid code requirements and guidelines for compliance verification. The study in Ref. [6] explored the evolving landscape of grid code compliance in the wind energy sector. The research focused mainly on component and subsystem-level testing, rather than on the regulatory requirements themselves. Similarly, the study in Ref. [7] provided an in-depth analysis of grid code compliance verification, with a primary emphasis on model validation and simulation-based compliance. However, a comprehensive study specifically exploring grid code requirements and guidelines for compliance testing remains absent in the literature.

During the last decade, many researchers studied the role of grid-forming IBRs in the inverter dominant power grids, and it is still an active research area for both academia and industry [8,9]. Most existing reviews on GFM IBRs focus on advance control methodologies [10,11]. There are very few studies that examined GFM functional capabilities, specifically focusing on GC requirements. The study in Ref. [12] review different grid codes, white papers, and technical documents on GFM functional specifications. Similarly, the study in Ref. [13] examined the role of GFM IBRs in future renewable-rich power systems and discussed core functional specifications for GFM inverters. Although both studies provide valuable insights into the functional requirements expected of the GFM inverters, they do not explicitly address how these specifications are reflected or mandated within existing grid codes.

1.2. Contributions

To address this gap in the existing literature, this paper presents a comprehensive review of grid code requirements regarding GFM inverters and grid code compliance testing. Throughout the review process, key references from the European regulation NC RfG 1.0, NC RfG 2.0 (amendment proposal), and ENTSO-E guidelines are presented. Current trends in grid code evolution and harmonization efforts in Europe are discussed in detail. The primary focus is on European grid codes; however, various national and international grid code requirements are also discussed in detail for comparison.

The motivation for this review stems from the continuous evolution of GCs, which are constantly updating to support the transformation of modern IBR dominant power systems. This paper provides a detailed literature review of current grid code compliance verification methods, particularly those recommended by ENTSO-E and the NC RfG. Based on the guidelines outlined in various European, national, and international standards, this review addresses several key research questions, such as: Which compliance method provide optimal balance between cost, accuracy, scalability, time-to-market, and neutrality? Which method is most appropriate for verifying compliance with specific grid code requirements? What are the modelling requirements for simulation-based testing? What are the model validation challenges, and what are the potential strategies to address these challenges? What are the key manufacturers' reasons for non-compliance? And what is the state of the art in the grid code compliance testing?

In addition, this paper systematically examines grid code requirements for core GFM functional specifications, including voltage source behavior, inertia emulation, fast fault current injection, sink for harmonic and unbalance, and oscillation damping. Furthermore, various simulation-based test frameworks for the compliance verification of core grid-forming capabilities are discussed in detail. Lastly, the study addresses various open research questions related to GFM integration, by drawing insights from recent technical reports, white papers, and grid codes.Table 1 presents a comparison between the current study and prior review studies.

The paper is structured as follows: Section 2 outlines grid code development and harmonization effort in Europe. In Section 3, grid code requirements and methodologies for compliance verification are explored. Section 4 provides a comprehensive review of GC requirements for grid forming IBR and discusses various open research questions related to GFM integration. In Section 5, several critical challenges, recommendations and future research directions are discussed, while section 6 concludes the research.

2. Grid code development and harmonization efforts in Europe

This section provides a detailed discussion on grid code development and harmonization efforts across Europe. The key research questions discussed are: What are European grid codes and how they are evolving? What is the convergence-level of NC RfG regulation? What are the major reasons for non-harmonizations in Europe. In this review, the term power generating module (PGM) is used to represent both synchronous generators and inverter-based generators. In contrast, the term Power Park Module (PPM) is specifically used for IBRs, in line with European grid code terminology.

2.1. European grid code framework

2.1.1. European Network codes on grid connection (CNCs)

The European Connection Network Codes (CNCs) were developed by ENTSO-E in coordination with the Agency for the Cooperation of Energy Regulators (ACER) and adopted as EU regulation by the European Commission in 2016. The three grid connection network codes include the Network Code on Requirements for Generators (NC RfG), the Network Code on Demand Connection (NC DC), and the Network Code on High Voltage Direct Current (NC HVDC). The NC RfG, also known as EU regulation 2016/631, establishes harmonized set of technical, operational, and performance requirements that generating units must satisfy prior to grid connection [14].

The NC RfG regulations are developed to ensure power system stability and operational security within the synchronous areas of Europe. Synchronous areas are the regions in Europe where national grids are interlinked and operate at same frequency. Europe is divided into five synchronous regions, each with distinct operational requirements. Accordingly, under the NC RfG, generators are classified in four categories (i.e. Type A, B, C, and D) based on the capacity thresholds which vary depending on synchronous areas (Table 2).

According to ENTSO-E, NC RfG requirements can be broadly classified into two categories: Exhaustive requirements and non-exhaustive requirements [15]. Exhaustive requirements are fixed parameters that must be uniformly applied across EU member states without modification at the national level, e.g., frequency ranges, limited frequency

Table 1
Comparison of relevant review studies.

Reference	Requirements for compliance testing	GFM functional specifications	Requirements for GFM	NC RfG 1.0 and 2.0	ENTSO-E guidelines
[6]	✓	×	×	×	×
[7]	✓	×	×	×	×
[12]	×	✓	×	×	×
[13]	×	✓	×	×	×
This study	✓	✓	✓	✓	✓

Table 2
Generator capacity thresholds for type A,B,C and D PGM.

Synchronous region	Lower limit for type A	Maximum lower limit for type B	Maximum lower limit for type C	Maximum lower limit for type D
Nordic	0.8 kW	1.5 MW	10 MW	30 MW
Baltic	0.8 kW	0.5 MW	10 MW	15 MW
Ireland	0.8 kW	0.1 MW	5 MW	10 MW
Great Britain	0.8 kW	1 MW	50 MW	75 MW
Continental Europe	0.8 kW	1 MW	50 MW	75 MW
	and	and	and	or
Voltage Limits	Below 110 kV	Below 110 kV	Below 110 kV	At least 110 kV

sensitive mode requirements, voltage ranges, etc. In the case of non-exhaustive requirements, network codes define parameter ranges rather than fixed values, allowing national regulatory authorities some flexibility in selecting parameter values within the specified ranges.

2.1.2. *EN 50549 standard and ENTSO-E Implementation Guidance Documents*

At the European level, EN 50549 standards and ENTSO-E Implementation Guidance Documents (IGDs) play a crucial role in ensuring the harmonized implementation of non-exhaustive requirements. EN 50549 1 & 2 defines technical requirements for the grid connection of type A and B generating modules, respectively [16,17]. EN 50549, prepared by CENELEC, is aligned with both NC RfG requirements and current technical market needs. This regional standard complements the exhaustive requirements of the NC RfG and serves as a reference document for national authorities in defining non-exhaustive requirements. By 2025, all European national standards that conflict with EN 50549 had to be withdrawn [18].

Since 2016, ENTSO-E has played an active role in the development of IGDs to promote harmonized yet flexible implementation of CNCs across EU member states [19–21]. The primary goal of IGDs is to provide clarity on national implementation of the CNCs while allowing room for country-specific adaptations. Both EN 50549 and the IGDs can be served as technical references for connection agreements between Related System Operators (RSOs) and Power Park Module (PPM) manufacturers. Fig. 1 shows the harmonized grid code implementation in Europe. It is worth noting that, in addition to these regional standards and guidance documents, national grid codes also play a critical role by clearly defining grid connection requirements tailored to their specific national contexts.

2.2. *Grid code harmonization in Europe*

Grid code harmonization refers to the process of aligning technical and regulatory requirements across different electricity networks to ensure efficient, stable, and secure power system operations [23]. As renewable energy integration and cross-border electricity trade increase, the need for standardized grid codes has become crucial. The NC RfG plays a crucial role in this process by establishing technical requirements that are applicable across all EU member states. Although complete harmonization has not yet been achieved, the implementation of the CNCs represents a significant step forward in establishing a cohesive regulatory framework for Europe’s energy transition. The considerable TSO coordination at the ENTSO-E level also plays an important role in the harmonization of GC requirements in Europe. Furthermore, the European stakeholders are actively shaping the second iteration of the EU Network Codes (NC RfG 2.0), with the goal of further streamlining technical requirements and reducing market entry barriers for electricity producers [24]. Key milestones in the European-level grid codes are illustrated in Fig. 2.

2.2.1. *Convergence level of NC RfG*

Convergence refers to the degree of alignment between national implementations and the NC RfG requirements. A high convergence level (close to 100 %) means that most countries have adopted the requirement without significant deviations. A low convergence level

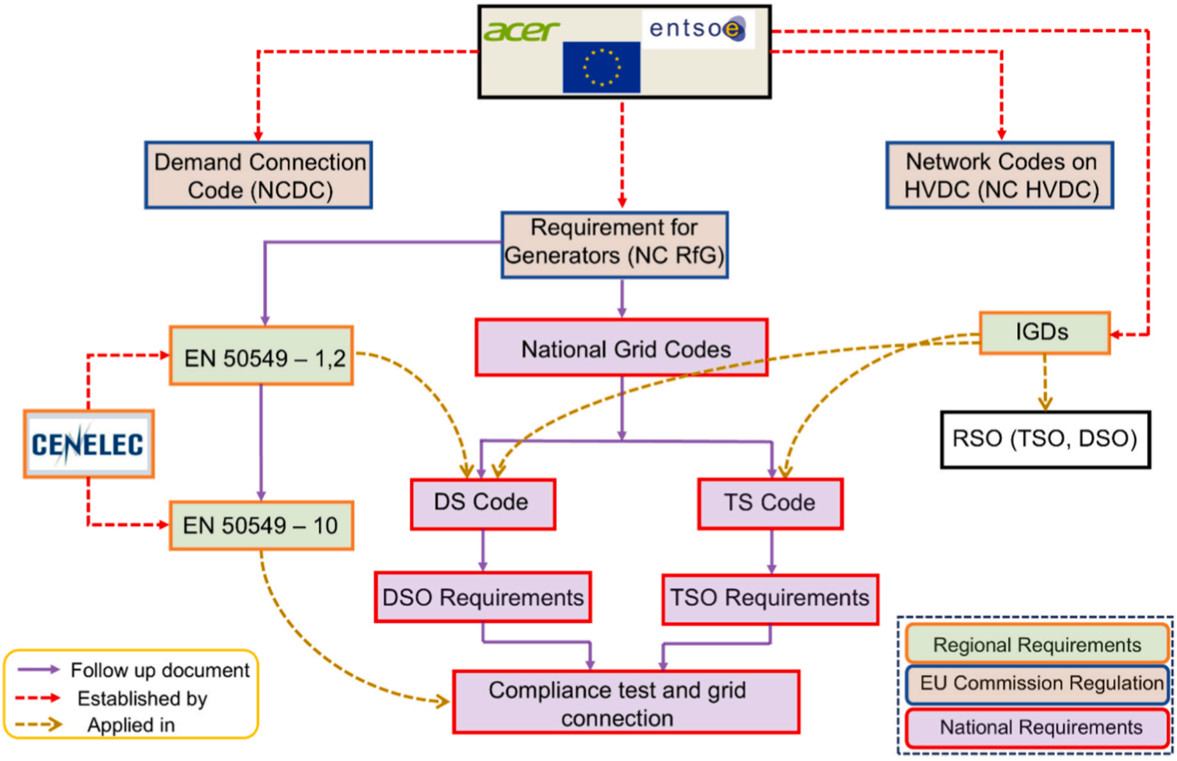

Fig. 1. Grid Code implementation in Europe [22].

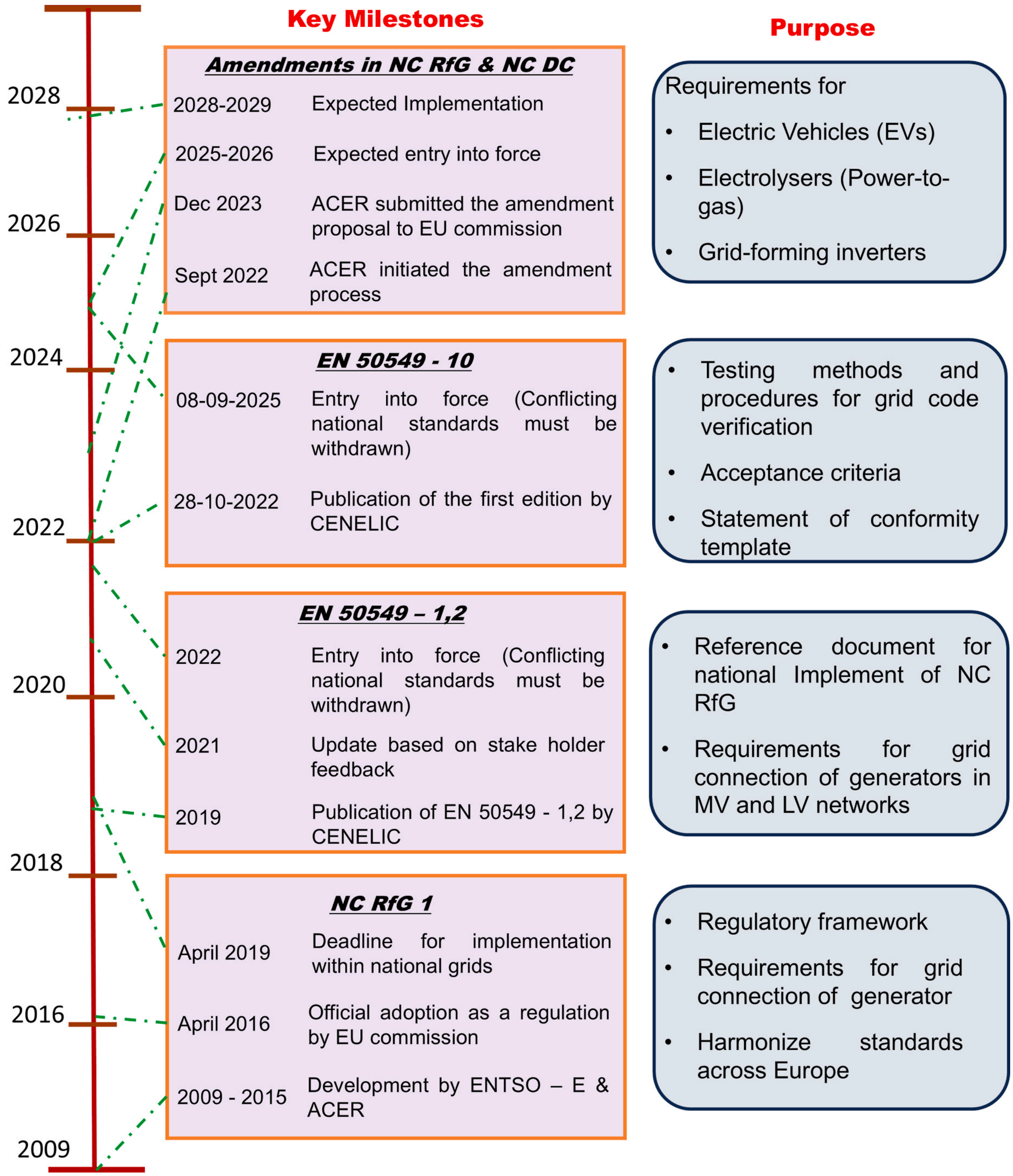

Fig. 2. Key milestones in European grid codes

suggests that countries have implemented the requirement with varying parameters or additional conditions. According to Ref. [25], the average convergence level of NC RfG requirements in Europe is 84 %. Similarly, the convergence level of EN 50549 in European member states is 52 %. Based on ENTSO-E guidance document [26] and reference [25], Table 3 classifies various NC RfG requirements as exhaustive or non-exhaustive and also indicates their respective convergence levels.

2.2.2. *Reasons for non-harmonization*

One of the major reasons for lack of harmonization is the presence of non-exhaustive requirements in CNCs, which necessitate additional specifications at the national level. The national implementation of non-exhaustive requirements has been successfully carried out; however, different countries have adopted varying approaches, reflecting the degree of flexibility explicitly permitted under the regulation. Another notable issue is the diversity in defining capacity thresholds for type A and B PGMs. A PGM classified as Type A in one country may be categorized as Type B in another European country.

For example, the type A/B threshold in Italian grid codes is 11.08 kW, while in Finland the threshold is 1000 kW [27]. This means that a 200-kW generator is categorized as type B in Italy and type A in Finland. As a result, the same PGM must satisfy additional technical requirements in Italy that are not needed in Finland. This lack of harmonization makes it challenging for manufacturers to sell their products across the EU, as products may be treated differently along the European borders. Furthermore, the lack of standardized testing, model validation, or

Table 3
NC RfG requirements and convergence level.

Requirements	NC RfG Article	Exhaustive/non-exhaustive	Convergence (%)
Frequency range	13 (1)	Exhaustive	97 %
Rate of Change of Frequency (ROCOF)	13 (1)	Non-Exhaustive	97 %
Limited frequency sensitivity mode-over frequency	13 (2)	Exhaustive	72 %
Limited frequency sensitivity mode-under frequency	15 (2)	Exhaustive	93 %
Fault ride through (below 110 kV)	16(3)	Non-Exhaustive	86 %
Reactive power capability at max capacity	18 (2) b	Non-Exhaustive	83 %
Reactive power capability below max capacity	18 (2) c	Non-Exhaustive	100 %
Simulation models	54	Non-Exhaustive	79 %
Loss of stability	20	Non-Exhaustive	41 %
Post fault active power recovery	17(3)	Non-Exhaustive	97 %
Rate of change of active power	15(2)	Non-Exhaustive	97 %
Reactive power control modes	21 (3)	Non-Exhaustive	100 %

certification procedures leaves room for divergent national compliance approaches. To overcome these issues, European stakeholders are actively shaping the second iteration of the EU Network Codes (NC RfG 2.0), with the aim of enhancing harmonization, streamlining technical requirements, and reducing market-entry barriers for manufacturers.

3. Grid code requirements for compliance testing

In this section, based on the guidelines provided by national and European standards, we aim to address key questions, such as: What are the methods for grid code compliance? Which methods are appropriate for verifying specific grid code requirements? What are the requirements for simulation models? And what is the current state of the art in grid code compliance testing? Which compliance method provide optimal balance between cost, accuracy, scalability, time-to-market, and neutrality? Which method is most appropriate for verifying compliance with specific grid code requirements? What are the modelling requirements for simulation-based testing? What are the model validation challenges, and what are the potential strategies to address these challenges? And what is the state of the art in the grid code compliance testing?

3.1. Grid code compliance methods

Under the NC RfG, achieving grid code compliance is a mandatory requirement for all PGMs seeking grid connection. Compliance testing is not required only at the moment of grid connection; rather, it can be conducted wherever reasonable during planning (help identify potential compliance challenges), development (simulation studies and component testing), Implementation (onsite testing), and operational (monitoring and retesting after modification) stages of the plant lifecycle [28]. According to NC RfG, grid code compliance can be demonstrated using equipment certificates, validated simulation models, and physical tests [29] (see Fig. 3).

Physical testing (on-site or laboratory) is considered the benchmark for high fidelity in grid code compliance. On-site tests are conducted during the commissioning phase of the power generating facility, before the final connection to the grid is activated. Unlike type tests, which verify the compliance of individual components, field tests assess the performance of the entire power generating facility under real operating conditions. On-site tests provide the highest level of fidelity and assurance that the PGM will not pose any risk to the grid stability.

However, physical testing is costly, time-consuming, provides low coverage (limited range of test conditions) and has low reusability. Furthermore, there are many technical challenges regarding the availability of test setups (FRT containers etc.), equipment rating and increasingly complex GC requirements. Field testing is also limited by the variations in ambient conditions and potential impacts on the grid. Therefore, a balanced approach is essential. Most of the compliance burden is ideally addressed earlier using validated simulation models and equipment certificates, which reduce the need for repeated testing. However, on-site testing must not be omitted entirely. It is the only practical and effective method to observe and validate how the entire plant interacts with the grid.

The study in Ref. [30] demonstrates in-field compliance testing of a solar PGM. The PV system is connected to a real distribution network, and test signals are digitally injected to verify compliance with NC RfG requirements. The research highlights various practical challenges regarding in-field compliance testing due to variability in solar irradiance and difficulties in testing reactive power support capabilities under fluctuating conditions. To overcome these challenges, the paper proposed combining various compliance methods, such as field testing, lab testing, and equipment certificates. The authors concluded that it is not feasible to verify all grid code requirements through field testing. Similarly, reference [31] used lab-based testing to verify battery storage compliance with Danish grid code requirements. The study concluded that storage system demonstrated fast dynamic response and was compliant with limited frequency sensitivity mode (LSFM), absolute power constraint and ramp rate constraint GC requirements.

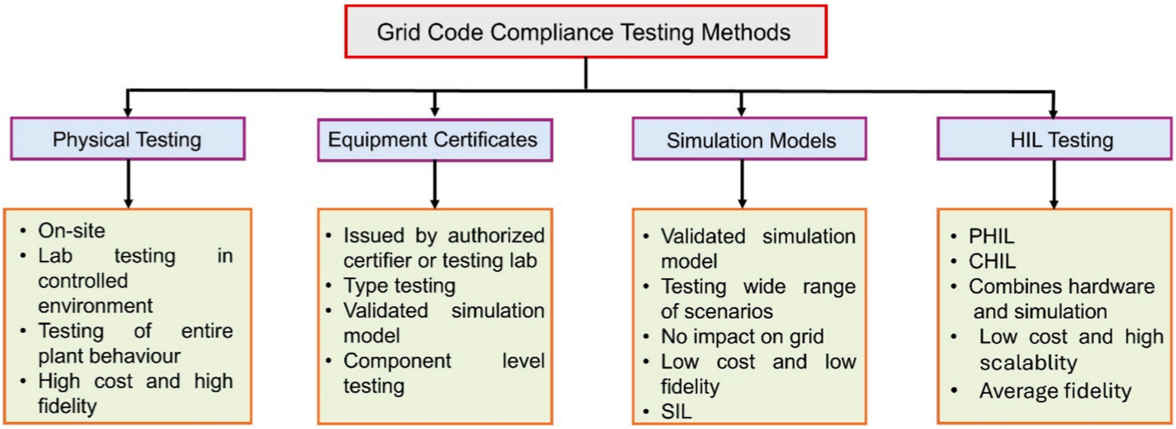

Fig. 3. Grid code compliance methods

An equipment certificate (EqC) is a formal, standardized document issued by an authorized certifier, based on type tests and validated simulation models supplied by manufacturers [32]. EqCs consolidate important information such as type test results, operating limits, parameter settings, simulation results, etc. into an official document that serve as a reference for compliance assessment. Facility owners can demonstrate partial or full compliance by using this third-party certification approach. The study in Ref. [22], uses a grid emulator based programmable lab test platform to verify compliance of three commercially available PV inverters against NC RfG and EN 50549-1 requirements. The research recommended the use of equipment certificates as an effective method for compliance verification.

EqCs reduce the time and cost and add credibility, neutrality, and transparency to the compliance process [32]. However, there are certain limitations such as lower fidelity compared to field testing and limited availability of authorized certification laboratories. In addition, this method certify compliance of components or units but not of entire power generating module. It means that in cases, EqC may partially fulfill compliance requirements and additional compliance verification may be needed at PGM level. Moreover, the related system operator retains the authority to accept, request further verification, or even reject the use of EqC if it does not sufficiently cover the applicable functionality at the connection point level.

Simulation-based testing bridges the gap between the physical tests and type tests by providing a low risk, cost effective and robust method for grid code compliance. Facility owners can verify compliance by using validated simulation models, especially where onsite testing is not applicable or reasonable due to the possible impact on the grid. By using validated electrical models, developers can test a wide range of scenarios without impacting the actual grid. These models replicate the plant's behavior based on known physical characteristics, controller logic, and electrical interfaces.Reference [33] investigated suitability of simulation models for GC compliance testing. An average inverter model was built to verify dynamic behavior under FRT conditions. Comparative analysis of simulations with experimental results show minor deviations, validating use of simulation-based testing for GC compliance verification. In Ref. [34], simulation-based method was used to assess compliance of a real solar power plant (type D) with Spanish grid codes.

Simulation-based testing offers several advantages, including low risk, low cost, high scalability, and broad test coverage. However, its effectiveness is limited by factors such as low fidelity, the limited availability of accurate manufacturer models, and challenges associated with model validation. Another simulation-based method for grid code compliance verification is software in the loop (SIL) testing. In comparison to traditional simulation, which provide high level testing by using build in blocks and idealized mathematical models, SIL simulations provide higher fidelity by testing actual VHDL, C, or C++ codes that will eventually run on the embedded hardware.

Another state-of-the-art method for compliance verification is hardware-in-the-loop (HIL) testing, which can be either Power Hardware-in-the-Loop (PHIL) or Controller Hardware-in-the-Loop (CHIL) [50]. HIL testing integrate actual hardware (e.g. inverter, controller) and real time simulation models (e.g. power system models, grid code functions) in a closed loop simulation environment to provide low cost, flexible, scalable, and high-fidelity solution for compliance verification. However, HIL testing also has its limitations, including issues with synchronization, scaling, and interface stability between software and hardware, as well as challenges related to data exchange, latency, and the dependence on the accuracy of the simulation models.

Fig. 4 shows a comparative analysis of various grid code compliance methods. From the earlier discussions, it is evident that each compliance method has its own benefits and limitations. No single compliance method achieves the optimal balance between cost, accuracy, scalability, time-to-market, reusability, and neutrality. Therefore, modern grid codes don't recommend a single compliance method for verifying all grid code requirements. Grid code compliance can be best achieved if all

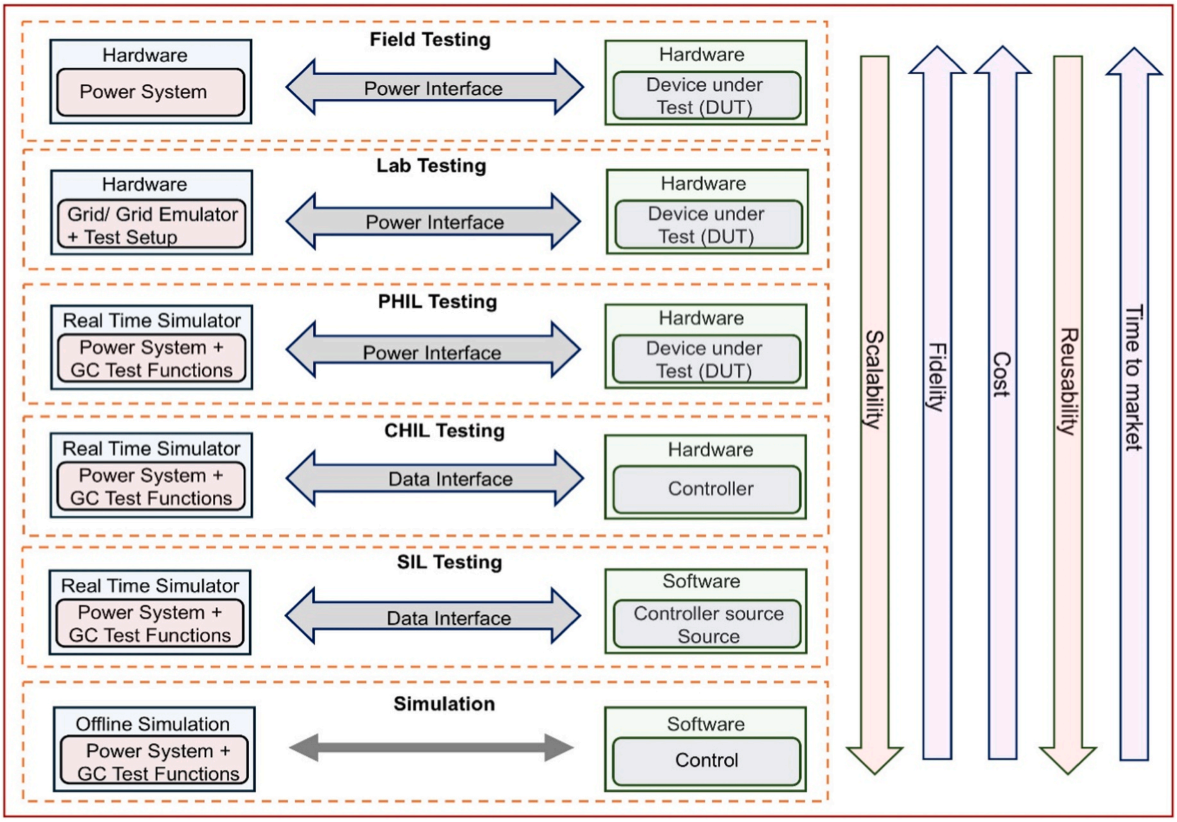

Fig. 4. Summary of Compliance Verification methods

Table 4
ENTSO-E guidelines on Compliance Verification Methods.

NC RfG requirements – capability and compliance verification		Compliance assessment based on EqC and CVT/CVS		
Description of capability requirement	PGM Type	EqC (minimum requirement)		CVT/CVS PPM&SPGM
		PPM	SPGM	
Frequency Sensitive Mode (FSM)	C, D	T&S	T&S	Mandatory
Limited Frequency Sensitive Mode- Underfrequency (LFSM-U)	C, D	T&S	T&S	Mandatory
Fault ride-through capability <110 kV	B	S	S	–
	C	S	S	–
Fault ride-through capability ≥110 kV	D	S	S	–
Capability to take part in island operation	C, D	–	S	Cond
Quick re-synchronization capability	C, D	–	T	–
Fast fault current injection	B, C, D	Cond(S)	–	–
Reactive power capability at maximum capacity	C, D	–	T&S	Mandatory
Reactive power capability below maximum capacity	C, D	–	T&S	Mandatory
Reactive power control modes	B, C, D	T	–	Mandatory
Limited Frequency Sensitive Mode – Over-frequency (LFSM-O)	A, B, C, D	T for A; T & S for ≥ B	T for A; T&S for ≥ B	Mandatory (≥ C)
Synthetic inertia during very fast frequency variations	C, D	Cond(S)	–	–
Recovery of active power after a fault	B, C, D	S	S	–
Black start capability	C, D	–	Cond(T)	Cond
Active power controllability	C, D	T	–	
Frequency restoration control*	C, D	Cond (S)	Cond (S)	Mandatory
Power oscillation damping control*	D	Cond (S)	Cond (S)	Mandatory
Reactive power capability at maximum capacity	C, D	T&S	–	Mandatory
Reactive power capability below maximum capacity	B, C, D	T&S	–	Mandatory

*PPM: Power Park module, *SPGM: Synchronous power generating module, *CVT: Compliance verification by testing, *CVS: Compliance verification by simulation, *Cond: Conditional, *S: Simulation, *T: Tests

available test strategies are combined: type tests by independent testing bodies, on-site commissioning tests run for each individual project implementation, and simulation tests and HIL-based test in the design and connection phases of a project.

3.2. ENTSO-E and NC RfG guidelines for compliance testing

Under the NC RfG regulation, initial compliance shall be demonstrated during the operational notification procedure. For type A PGMs, due to their small size and low impact on the grid, the procedure is relatively simple, and compliance can be demonstrated using EqCs. For type B and C, the grid codes require more detailed submission, including technical data, equipment certificates, validated simulation models, and test results to the RSO. Due to their increased size and potential impact on the grid, Operational Notification Process (ONP) is more complex for type D PGMs.

For type D PPMs, the ONP is divided into three stages. In the first stage, named Energization Operational Notification (EON), PGM is allowed to connect to the grid, but generation is not permitted. To receive EON, facility owners are required to submit installation designs, operational manuals, and key settings such as control and protection configurations to the RSO. In the second stage, Interim Operational Notification (ION), PGM is allowed to generate electricity for a limited duration, i.e., up to 24 months. Receiving ION requires submitting detailed parameters, compliance certificates and a plan for physical compliance testing, etc. The final stage is the Final Operational Notification (FON), which means PGM is allowed to generate electricity without restriction. As part of the FON, the facility owner and the RSO must also agree on how compliance will be monitored in the future. Long-term online monitoring is important during the life cycle of the PPMs. A PPM may fail to comply with grid code requirements during real grid events despite passing initial compliance test [35].

In section 3.1, various compliance methods, i.e., Equipment certificates, validated simulation models, and on-site testing, were discussed. Which compliance method is best suited for verifying compliance with various PPM requirements specified in the grid codes? Modern grid codes don’t recommend a single compliance method for verifying all grid code requirements. ENTSO-E addresses this question by providing guidance in Table 4.The table outlines specific requirements to be verified and identifies the most appropriate methods for demonstrating compliance [36]. The table indicates that, for most requirements, equipment certificates can be used to demonstrate compliance, particularly for small Power Generating Modules (Types A and B). However, for certain requirements, such as limited frequency sensitivity mode and active/reactive power capabilities, additional compliance verification using simulation models (CVS) or on-site testing (CVT) is mandatory, especially for large generators (Types C and D).

The RfG mandates a binding framework for compliance verification, including operational notification procedures and ongoing monitoring [37]. However, it does not specify standardized testing, model validation, or certification procedures, leaving room for divergent national approaches. Some countries, such as Germany and Spain, provide detailed guidelines regarding compliance and certification schemes in their grid codes. Overall, the state of compliance verification across Europe is suboptimal, with an average coverage level of only 51 %. In most national standards, clear guidelines for testing and certification procedures are lacking. This highlights the urgent need for the development of standardized frameworks that explicitly define compliance requirements and verification procedures. At European level, EN 50549-10 can be used as a reference document to demonstrate grid code compliance. EN 50549-10 provide clear guidelines regarding testing methods (equipment certificate, onsite testing, Hardware-in-the-Loop testing, simulation models), testing procedures, acceptance criteria, statement of conformity (template) for all the grid connection requirements specified in EN 50549-1 & 2 [38]. Other similar standards that provide testing guidelines include UL 1741, IEEE P2800, IECRE OD-009, and IECRE OD-501 etc.

3.3. *Compliance by simulation*

Simulation-based testing offers several advantages, including low risk, low cost, high scalability, and broad test coverage. As outlined in Table 4, the majority of grid code requirements can be verified using simulations. Moreover, under the NC RfG regulation, facility owners are required to submit validated simulation models to the relevant system operator, particularly for Type C (rated power above 10 MW) and Type D PGMs. These considerations underscore the critical role of accurate and validated simulation models in the compliance verification process. Therefore, in this subsection we will discuss modelling and validation requirements as specified in various grid codes.

3.3.1. *RMS, EMT and FDI modelling requirements*

Under the NC RfG regulation, relevant system operators have the right to demand root mean square (RMS), electromagnetic transient (EMT) or frequency dependent impedance (FDI) models from the power-generating facility owners [39]. The key features of these models are presented in Table 5. According to ENTSO-E, RMS models should be capable of representing system behavior up to a frequency range of 3 Hz and must include detail representation of power electronic converters, control systems and protection functions. The model should be open source to facilitate cross border stability analysis. EMT models must be capable of accurately reproducing PPM responses during both normal and faulty conditions within a frequency range of 0.1 Hz–2500 Hz. These models are required to include plant level control, protection functions, frequency dependent impedance and transformer models. For FDI models, RSO can demand impedance profile of a PPM within a frequency range of 5 Hz–2500 Hz (up to 9000Hz, if required). The model should be valid for both positive and negative phase sequence and it must include the impact of control and measurement systems on the output impedance. Encrypted RMS and EMT models are allowed, however RSO must specify encryption requirements e.g. source code, signal interface and model structure requirements.

Table 6 presents the EMT modelling requirements as outlined in various national standards. Australian Energy Market Operators (AEMO) and Electric Reliability Council of Texas (ERCOT) demand EMT models for all type of generators especially under weak grid conditions, while Fingrid (Finland) demands EMT models for type C and D PPMs. The preferred simulation tool for EMT modelling is PSCAD and the accepted compiler is Intel Fortran. The model can be submitted in precompiled and encrypted form. However, all grid codes demand validated models with block diagrams, parameter details, and manuals. Simulation time step requirements vary in grid codes with AEMO allowing time step of 1 μs while Fingrid allow a maximum time step of 10 μs.

3.4. *Model validation*

Model validation is the final and most technically demanding stage of the model development process. Grid codes mandate that simulation models used for compliance verification undergo rigorous validation to ensure accurate representation of system dynamics, verification of underlying assumptions made during model development, and clear identification of the model's operational limits. A simulation model is considered valid if the difference between simulation results and measured data stayed within a specified tolerance limit. The acceptable tolerance range varies between 5 % and 15 % across different regional and national standards. Model validation is an iterative process during which model parameters and/or model structure may be modified to

Table 5
Key features of RMS,EMT and FDI modelling.

Key features	RMS modelling	EMT modelling	FDI modelling
Domain	Time domain average modelling	Time domain instantaneous modelling	Frequency domain modelling
Complexity	Low (large time steps)	High (small time steps)	Moderate
Computation speed	High	Low	Moderate
Frequency range	0–3 Hz	0–10 kHz	5–2500 Hz
Applications	Stability analysis, power flow analysis, slow dynamic studies	FRT analysis, PE converter behavior studies, transients and harmonic analysis [40,41].	Stability analysis of inverter dominant grid, resonance and harmonic interaction studies [42,43].
Purpose	Long-term dynamic studies [44]	Fast transient studies and PE interaction studies	Analysis of Impedance variation with frequency

Table 6
Simulation model requirements in various standards.

Requirements	Fingrid [45]	Energinet [46]	AEMO [47]	ERCOT [48]
Submit model	Type C and D	Type D	All	Models require under weak grid and resonance conditions
Software	PSCAD 5.0.1 or above	PSCAD/EMTDC	PSCAD/EMTDC	PSCAD
Time step	10 μs	Not mentioned	1 μs	10 μs –20 μs
aggregation	Yes	Yes	Yes	Yes
Open/encrypted	Not mentioned	Precompiled and encrypted	Precompiled and encrypted	Precompiled and encrypted
Compiler	Intel Fortran/visual studio	Intel Fortran	Intel Fortran	Intel Fortran
Snapshot function	Yes	Yes	Yes	Yes
Initialize in	Less than 3 s	Less than 3 s	Less than 3 s	Less than 5 s

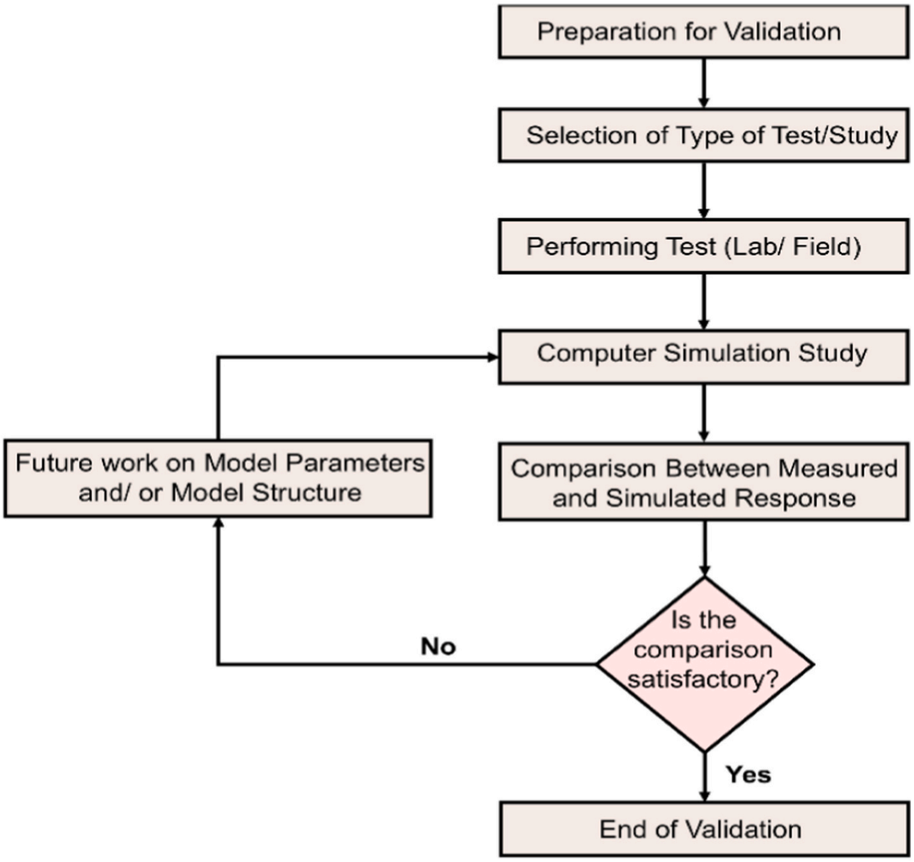

Fig. 5. Model validation process

best fit the event [49] (see Fig. 5). The quality of validation process is highly dependent on the data used for validating the model. Sources of data could be field measurements, laboratory test, accepted simulation models and HIL test systems [50].

3.4.1. *Model validation challenges*

Field measurements are widely regarded as most reliable option for model validation and are even considered mandatory in some countries, such as Germany. Field data can be obtained from induced events (tests during commissioning) or from actual system events (recording data from system operations). However, validating simulation model using field measurements is limited due to delayed data availability (until commissioning), high cost, inaccurate measurements and differences between model development and test conditions. An alternative solution is to generate data through laboratory testing, which offers controlled conditions and high-quality measurements. However, this method has its own limitations such as high cost, scalability, simplified conditions and inability to capture real world dynamics such as weak grid scenarios and long-distance interactions.

Another major challenge arises from toll-specific numerical discrepancies such as time-step sizes, solver accuracy and algorithm precision, etc. These discrepancies may result in unnecessary model tuning and rejection of valid models. The IEC 61400-27-2 recommend using both play-back method (open loop, strong grid) and full grid simulation (closed loop, include grid interactions) for model validation [51]. However, in practice, only one of these methods is used which limits the robustness of the validation process. Moreover, advanced aggregation methods that can accurately capture collective dynamic behavior of DERs are missing. Although GCs allow aggregation (Table 6), currently there is no universally accepted aggregation method. Another major challenge is the absence of standardized model valid procedures in grid codes [52].

3.4.2. *Strategies for addressing model validation challenges*

To address these challenges, detailed guidelines for model validations need to be formulated with consensus from all stakeholders. The quality of validation data can be improved by using high-fidelity instrumentation with sufficient bandwidths to capture transients and a sampling rate of at least 10 kHz. Furthermore, hybrid validation methodologies, combining both play-back and full-grid simulations, should be adopted to ensure robust validation process.

Moreover, there is a growing need to develop advanced aggregation methods that can accurately capture collective dynamic behavior of DERs [53]. The study in Ref. [54] integrated DER models namely artificial intelligence models, regression-based models and equivalent electric circuit models through linear optimization to develop a composed aggregated DER model. Case studies conducted on IEEE 69 bus system demonstrated that the proposed aggregated model accurately represent collective DER behavior at feeder level with an average root mean square error of 0.3 % and remain robust during load variations and model simplifications. In Ref. [55] an aggregative PV model was built in DigSilent Power Factory software to verify compliance with Spanish grid codes. Simulation results show that aggregated model shows the same behavior as detailed model with a deviation of less than 0.1 %. Also, in comparison to detailed model, aggregated model is ten times faster to simulate, showcasing its significance as a scalable and practical solution for simulation-based compliance verification.

Model validation can also be achieved by comparing developed models with already accepted simulation models e.g. simple RMS models can be validated against well accepted EMT simulations. The current trend is to use Hardware-in-the-Loop (HIL) setups for validating simulation models [56]. HIL testing combine the benefits of experimental testing and software simulations to provide a low cost, flexible, and efficient option for model validation.

In [57], Power Hardware-in-the-Loop setup is used for the model validation of an active distribution network. In Ref. [58], EMT model of a type 4 wind turbine is validated by benchmarking the simulation results with HIL test results. The EMT model, built in PSCAD, was validated against low voltage ride-through (LVRT), High Voltage Ride-Through (HVRT), system strength and phase jump requirements specified in ERCOT standards. The study in Ref. [59], implement generic and detailed wind turbine models using MATLAB/Simulink and PSCAD/EMTD software respectively. The model was validated against field measurements from an actual Gamesa wind turbine located in Spain. Under LVRT scenarios detail models show acceptable compliance with Spanish grid codes. However, generic models show inaccuracies during transient periods particularly due to inaccurate modeling of transformer inrush current behavior.

Also, cross-platform model benchmarking i.e. running same test scenarios across different platforms such PSCAD, Power Factory, MATLAB/Simulink, can help detect toll-specific numerical discrepancies. Running identical models on multiple platforms enhances confidence in their accuracy while ensuring software neutrality and portability. Furthermore, advanced technologies such as digital twins can support model validation and calibration by emulating converter performance under various grid conditions [60,61]. ABB white paper in Ref. [62] proposed that utilities, aggregators and power generation companies must provide detailed, high-fidelity power system simulation reports based on ‘digital twins’.

3.5. State of the art in grid code compliance testing

Physical testing (on-site or laboratory) is considered the benchmark for high fidelity in grid code compliance. However, physical testing is costly, time-consuming, provides low coverage (limited range of test conditions) and has low reusability. Furthermore, there are many technical challenges regarding the availability of test setups (FRT containers etc.), equipment rating and increasingly complex GC requirements. An alternative solution is to use validated simulation models for GC compliance verification. Testing using simulation provides benefits, such as low cost, high scalability and coverage but test fidelity is compromised. This situation demands an alternate compromised solution for compliance testing. One such solution is HIL testing, which is also a state-of-the-art approach not only in research but also in industry.

3.5.1. Use of real-time simulators

Real-time simulators (RTS) mimics the dynamics of a physical system (e.g. inverter, EV, power grid etc.) in real time, i.e. simulation progresses at the same speed as actual time. Some examples of RTS are dSPACE, OPAL-RT, Typhoon HIL etc. In power system studies, real-time simulation can be classified into two broad categories, i.e., (1) HIL real-time simulation and (2) full real-time simulation (e.g. Software in the loop (SIL), Model in the loop (MIL), etc.).

3.5.2. Hardware-in-the-loop (HIL)

HIL testing combines the benefits of physical testing (high fidelity, use of actual hardware) and simulation base testing (low cost, scalability and coverage). HIL testing integrate actual hardware (e.g., inverter, controller) and real time simulation models (e.g., Power system models, grid code functions) in a closed loop simulation environment to provide low cost, flexible, scalable, and accurate solution for compliance verification. If the actual hardware is the controller that interact with the simulation, then it is called CHIL. If Device Under Test (DUT) (e.g., full power converter) is connected to a RTS using a power interface (amplifier or grid emulator), then this setup is called Power Hardware-in-the-Loop (PHIL). EN 50549-10 considers HIL, specifically Controller Hardware-in-the-Loop (CHIL), as a valid method for compliance testing. The standard provides guidelines on the testing conditions, simulation models, firmware of the control unit and communication interfaces.

Recently several studies investigated the use of CHIL and PHIL test setups for GC compliance testing. In Ref. [28], a modular HIL testing platform was introduced to investigate the stability of an IBR dominant medium voltage CIGRE benchmark grid under fault and grid disturbance conditions. A unifiable CHIL and PHIL platform is developed in which a real time grid simulation model is connected to an inverter hardware (DUT) through a power amplifier. The study in Ref. [63] investigated GC compliance of a type D wind farm facility located in Poland by using HIL testing. The wind farm, modelled in a real time simulator, is interfaced with the protection relays (hardware) in a closed loop to verify LVRT requirements as specified in NC RfG regulation. In Ref. [64], a CHIL test setup is utilized to evaluate compliance of a grid-connected PV inverter under German GC requirements. Comparison of CHIL results with actual lab test results shows a very small deviation (within 2 %), validating the reliability of CHIL-based certification.

In [65], PHIL test setup is utilized to verify LVRT capabilities of a 5 kVA Danfoss inverter (GFM & GFL) considering German (FGW TR3) grid codes. In Ref. [66], CIGRE test grid modelled in OPAL RT simulator is connected to a 600 kW Flywheel energy storage system (DUT) through a 200 kV power amplifier to create a PHIL test setup. The results verify compliance of frequency support capabilities with German grid codes (VDE-ARN). The study in Ref. [67] proposes a fully automated System Validation Platform (SVP)-based PHIL test setup for verifying IEEE 1547 voltage, frequency and ROCOF capabilities of commercially available PV inverters. During each compliance test, SVP send disturbance signals and RTS apply these to the DUT using a grid emulator. The results show that inverters are non-compliant with IEEE 1547–2020 requirements, because they are certified and configured under earlier IEEE 1547–2014 standard.

3.5.3. Software in the loop (SIL)

SIL is a simulation technique, in which a control algorithm in the form of compiled software code is tested by connecting it to the RTS model of the plant without involving actual hardware. In comparison to traditional simulation, which provides high level testing by using built-in blocks and idealized mathematical models, SIL simulations provide higher fidelity by testing actual VHDL, C, or C++ codes that will eventually run on the embedded hardware. Several research articles investigated the use of SIL simulations for testing control strategies in grid-connected systems. In Ref. [68], SIL simulations are used for GC compliance testing of unintentional islanding detection requirements specified in the IEEE 1547.1 standard. A simulated inverter laboratory provides a fast, low-cost, safe and flexible testing approach for GC compliance validation.

3.5.4. Use of grid emulators

En 50549-10 outlines verification procedure for testing various GC requirements, using a grid emulator. A grid emulator is a programmable AC power supply that can emulate real world grid behavior. Traditional lab setups such as power supplies, actual grid connections, and generators provide fixed voltage and frequency, lacking flexibility to emulate real-world grid scenarios for efficient GC compliance verification. Grid emulators provide a safe, controlled and repeatable testing environment for emulating various grid code conditions, such as weak grid, black start, frequency and voltage variations, faults and islanding. The study in Ref. [69], uses a lab test setup to verify compliance with IEEE 1547–2018 requirements. A grid emulator is utilized to emulate dynamic grid scenarios in a controlled lab environment. Table 7 provides a summary of the literature review on compliance testing methods discussed in section 3.

Table 7
Overview of the literature on compliance testing.

Ref	Method	Grid Code Used	Test Functions
[31]	Lab Test	Danish TF331	LSFM, LVRT
[70]	PHIL	European GC	FRT, Reactive current support, frequency regulation
[68]	Simulation (SIL)	IEEE 1547.1	FRT, Islanding detection
[71]	Lab Test + Grid Emulator	IEC 61850-90-7	FRT, Volt-var control, Frequency Regulation
[63]	HIL	European GC	LVRT
[57]	Model validation using PHIL	EU NC RfG (European)	LVRT, Reactive power support
[69]	Lab Test + Grid Emulator	IEEE 1547-2018	Voltage and frequency regulation, FRT
[65]	PHIL	FGW TR3 (Germany)	LVRT, Reactive power support
[35]	Site Test + Lab Data	Canadian GC	LVRT, Voltage regulation, Ramp rate limit, Power quality assessment
[72]	Simulation	NC RfG + EN 50549-10	Volt-var control, Active Power Curtailment
[30]	In-Field Test	NC RfG + EN 50549-2	Active & reactive power control
[73]	PHIL	Brazilian NBR 16149	FRT
[74]	Lab Test + Grid Emulator	NC RfG + Polish DSO	frequency regulation, LVRT, Power control
[33]	Simulation	–	FRT
[75]	HIL (CHIL + PHIL)	–	Inertia, Fault response
[66]	PHIL	VDE-AR-N 4105	Frequency support
[34]	Simulation	Spanish GC (NTS)	Frequency & Reactive power regulation
[76]	PHIL + Grid Emulator	EU RfG NC	LVRT
[55]	Simulation (Aggregation)	NC RfG + NTS	Active & reactive power capability
[64]	C-HIL	DIN VDE V 0124-100	LVRT, Frequency response
[58]	Model Validation using HIL	ERCOT Requirements	FRT, Phase Jump, system strength
[56]	Model Validation	ERCOT	LVRT, HVRT
[77]	Lab Test	IEC 61400-21 + FGW	Power Quality, FRT, Reactive power support
[59]	Model Validation	Spanish PO 12.3	LVRT, HVRT
[78]	Lab Test	EU NC RfG + Czech GC	Frequency Support
[67]	PHIL	IEEE 1547	FRT
[23]	SIL	South African GC	Voltage sags, Frequency regulation

4. Grid code requirements for grid-forming IBRs

This section systematically examines grid code requirements for core GFM functional specifications, including voltage source behavior, inertia emulation, fast fault current injection, sink for harmonic and unbalance, and oscillation damping. Furthermore, various simulation-based test frameworks for the compliance verification of core grid-forming capabilities are discussed in detail. Lastly, the study addresses various open research questions related to GFM integration, by drawing insights from recent technical reports, white papers, and grid codes.

4.1. *Grid-forming capability requirements*

Prior studies indicate that stability issues in power systems typically arise when the share of grid-following IBRs exceeds 65 % of total generation [79]. To enable higher renewable energy penetration, inverters must actively support the grid through GFM capabilities. However, the specific functionalities and performance requirements expected from

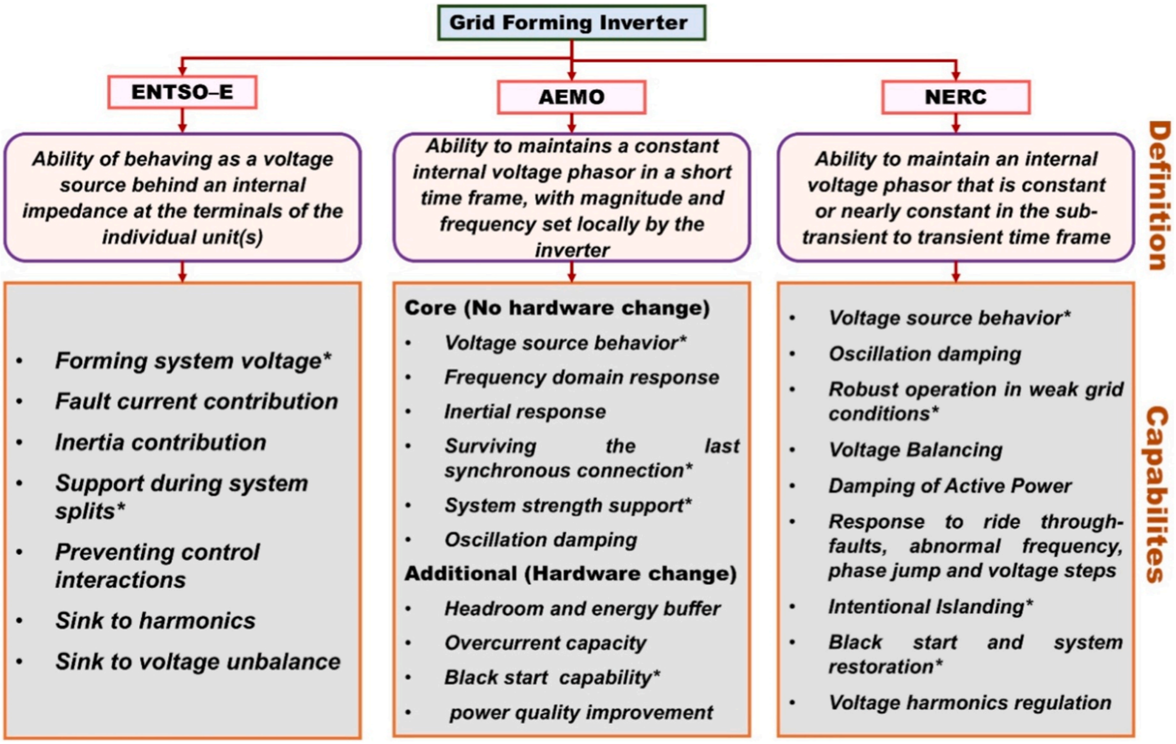

Fig. 6. Grid-forming IBR functional specifications

GFM implementations remain unclear and vary across different standards [80,81]. Moreover, there is currently no unified definition of a grid-forming converter, as various grid codes offer differing interpretations.

Fig. 6 provides an overview of GFM definitions and functional capabilities as outlined in the technical reports of the European Network of Transmission System Operators for Electricity (ENTSO-E) [82], Australian Energy Market Operators (AEMO) [83], and North American Electric Reliability Corporation (NERC) [84]. In addition to these, several other definitions exist across literature. Based on a comprehensive review of these documents, a generalized definition of a GFM resource can be stated as: *"A GFM resource, irrespective of system strength and within its current capability limits, should behave as a voltage source behind an impedance and sustain a constant or near constant voltage phasor at its terminal in the sub-transient to transient time period"*.

It is important to note that certain capabilities typically associated with GFM inverters, such as frequency response, fault current injection, harmonic absorption, unbalance mitigation, voltage angle control, and step response can also be achieved using GFL inverters. However, compared to GFL, GFM converters offer a significantly faster and nearly instantaneous response. Notably, beyond the first second of operation, distinguishing between a GFL and a GFM inverter becomes increasingly difficult. The capabilities that are unique to GFM behavior and can be provided only by GFM converters are indicated with an asterisk (*) in Fig. 6.

4.1.1. Voltage-source behavior

According to Article Y of the NC RfG 2.0, (a) A GFM PPM should be capable of behaving as a voltage source behind an internal impedance within specified current and power limits. (b) This voltage-source behavior is required not just during normal operation, but also when there are disturbances in the grid, such as faults or sudden changes. The magnitude and phase angle of the internal voltage source should remain nearly constant within the transient timeframe following a disturbance. (c) When operating at current limits, the PPM module shall be capable of operating in a stable manner. In cases where current limitations are necessary, the relevant system operator, in coordination with the relevant TSO, may specify additional requirements regarding active and reactive power supply at the point of connection.

Unlike GFL converters that control output currents, the main control objective of GFM converter is to control output voltage in the sub-cycle timeframe (NERC). *In case of voltage step changes the GFM inverter should respond instantaneously (less than* 5 ms*) to oppose the change in voltage* [GC 0137(GB), UK grid codes]. *The stability Pathfinder initiative under the UK National Grid specifies that GFM converter should be capable of withstanding large voltage angle change of 200° that last no longer than* 5ms *and 90° lasting no longer than* 60ms. *The draft further specifies a non-mandatory GFM capability of operating as a voltage source behind a reactance over a frequency band of* 5Hz *to* 1 kHz *before, during and after a fault* [85]. The study in Ref. [86] compares three GFM control topologies i.e. with no inner loop, with inner current control and with cascaded voltage and current control. The results show that GFM control with no inner loops exhibit the best voltage source behavior and maintain impedance passivity in the frequency range of 5 Hz to 1 kHz.

The study in Ref. [87] emphasis that internal voltage sources must be stiff with limited magnitude, phase and frequency dynamics. Slow dynamics is desirable for emulating stiff voltage source behavior. However, due to this the system may become sluggish and respond slowly during large disturbances, increasing the risk of stability and loss of synchronism. Conversely, fast dynamics enhances transient stability by quickly adapting to grid fluctuations but limits the converter's ability to behave as a stiff voltage source. To resolve this issue, the study in Ref. [88] proposes an adaptive fast/slow IVS (internal voltage source) control strategy which, switches between fast and slow dynamics based on real-time grid conditions and converter current margins. Under normal operating conditions, when there are sufficient current and stability margins, converters operate in slow IVS mode to provide full GFM services. When the disturbance pushes the system to current limits or large power angle deviations occurs, the controller transitions to fast IVS mode to enhance stability and prevent loss of synchronization. The study experimentally validated effectiveness of proposed control strategy in maintaining stable operation even under severe disturbances.

4.1.2. Fault current contribution

The objective of fault current contribution is to enhance grid stability and ensure reliable protection during faults. Sufficient fault current contribution prevents immediate voltage collapse and supports the correct operation of protection devices. According to ENTSO-E, *GFM inverters must maintain voltage during faults and should contribute sufficient fault currents to ensure the proper operation of protection systems.* However, this stiff voltage-source behavior may result in large fault currents, exceeding the hardware limitations of the inverter. Therefore, grid codes require controlled fault current injections (within GFM converter overcurrent capacity limits) to support grid voltage during faults. *If current limits are reached, the total apparent current shall be as close as possible to the rated value and must not fall below 95 % of the rated current (ENTSO-E)*.

GFM inverters are required to have fault-ride-through capability and should remain synchronized during transient grid faults and load variations. Like synchronous generators fault current contribution from the GFM converters should be instantaneous. Therefore, some national grid codes also emphasize fast fault current injections*, like GB stability-pathfinder draft, where fault current injections within 5 to* 30ms *is recommended. Also, German VDE AR-N 4110 mandate a fault current injection within* 30ms. *Under current limiting conditions, ENTSO-E allowed a delayed fault current injection, but not more than* 20ms.

AEMO specifies the ability to operate temporarily at *currents above continuous rating (*e.g.*, 150 % of the rated current for* 2s*)* as an additional capability for GFM inverters. Due to this capability, GFM inverters can support traditional protection schemes designed around synchronous generator (SG) fault levels. The study in Ref. [89] emphasis that under 100 % renewable penetration scenarios fast fault current within 5 ms is essential. The voltage-source behavior of the GFM inverter may result in large current injections during faults, forcing it to operate in a current limiting mode. According to ENTSO-E, there are two current-limiting options: a) switching to current control mode during faults, and b) current clipping. However, current clipping is usually not recommended as it may reduce harmonic performance. Current limiting is an active area of research, and various current limiters such as circular limiters [90], root mean square limiters [91] and elliptical limiters [92] are proposed in the literature. For further study [93,94], provide a detailed review of various GFM converter current-limiting schemes under LVRT and fault conditions.

4.1.3. Inertial response

Articles 21 and 22 of the NC RfG 2.0 include synthetic inertia contribution (within defined capability limits) as a non-exhaustive requirement for Type B, C, and D grid-forming power park modules. Additionally, Article 2 of the regulation defines synthetic inertia as a specified dynamic capability of a PPM that emulates the inertial response typically provided by conventional synchronous generators. Both GFL and GFM IBRs should be capable of providing synthetic inertia. GFL control requires frequency or ROCOF measurements for inertia provision. However, according to AEMO, *the inertial response of GFM inverters should be inherent, i.e., no frequency or ROCOF calculations*. This inherent behavior allows GFM inverters to provide a near-instantaneous inertia response by injecting or absorbing active power during system transients such as load variations, generation outages, or system splits. *Additionally, if configurable, the inertia constant of a GFM inverter is recommended to be set in a range wider than that of synchronous machines (ENTSO-E).*

According to ENTSO-E without additional inertia, the future inverter-dominant grids of central Europe may face a large number of systems split scenarios, resulting in unmanageable ROCOFs and possible system blackouts. Therefore, ENTSO -E project inertia proposes additional inertia provision by using storage, STATCOMs, and synchronous condensers etc., [95]. The study in Ref. [96] demonstrate that inertia characteristics of the GFM inverters are dependent on the level of damping; low damping results in high equivalent inertia, while high damping reduces inertia. To overcome this tradeoff, a lead-lag controller is proposed that decouples inertia and damping, allowing both to be tuned independently.

Several studies have explored the role of GFM and GFL inverters in enhancing frequency stability in low-inertia power systems [97,98]. The general consensus is that, compared to GFL inverters, GFM inverters provide superior dynamic performance, including better frequency nadirs and ROCOF profiles [99,100]. The study in Ref. [101] evaluates the synthetic inertia response of a 700 kW GFM energy storage converter under ROCOF and system split events. The inverter response was benchmarked against the ROCOF patterns provided by the ENTSOE. CHIL simulations and laboratory test results demonstrate the GFM inverter's capability to deliver a fast inertial response in compliance with grid code requirements, while maintaining stable operation under severe ROCOF conditions (±1 Hz/s) and system split events. Reference [102] presents real time PHIL simulations to validate the capability of the GFM converter in stabilizing a 240 MW MAUI power system under fault conditions and zero-inertia scenarios. The research concluded that in a low system strength scenario, 12 % of the total generation must be GFM to keep the system stable. Furthermore, the study in Ref. [103] criticizes the near-instantaneous (within 5 ms) inertial response requirement by NG ESO and considers it unrealistic and impractical under real-world operating conditions.

4.1.4. Damping oscillations

According to ENTSO-E, *a GFM inverter should be capable of providing positive damping to prevent unwanted oscillations and control interactions*. In power systems, resonance can occur due to passive (cable capacitances and transformer inductances) or active elements (control loop of other converters). These resonances pose a risk if they occur within the frequency range where the converter control is active, i.e., controller bandwidth. If a resonance falls within the control bandwidth, the converter may unintentionally amplify it instead of damping it. A GFC with a wide control bandwidth can interfere with or amplify these resonances, potentially causing instability in the system [104]. Therefore, grid-forming control (GFC) systems are required to limit their bandwidth in the 5 Hz and 1 kHz range.

According to Fingrid, *Grid-forming (GFM) control shall present positive resistance to the grid in the frequency ranges of 0–*47Hz *and 53–*250Hz *to avoid adverse interactions. It is especially critical that GFM operation does not diminish the damping of low-frequency inter-area oscillation modes in the 0.2–0.*5Hz *range.* Both the inverter and the grid exhibit frequency-dependent impedances. Connecting a GFM inverter to the grid introduces new resonance points. These resonant points occur at frequencies where the impedance curve of the inverter interacts with frequency-dependent grid impedance. According to ENTSO-E, *critical resonance risks arise when the inverter and grid impedance curves cross in magnitude, and their phase difference approaches 180°, leading to potential amplification of oscillations*. The amplification factor depends on the angle difference at the point of intersection. As this angle approaches 180°, the resulting resonance becomes increasingly pronounced. Therefore, AEMO recommended that *GFM inverters should ideally show an impedance phase angle between -90° and + 90°, at most frequencies from 10 Hz (Hz) to* 500Hz.

The study in Ref. [105] shows that due to inaccurate controller tuning, the phase margin at impedance crossover points approaches −180°, causing oscillation amplification instead of damping. A lead compensator is designed to reshape loop gains and improve the phase difference between the converter and the grid at impedance crossover frequencies. GFL converters with phase-locked loops for synchronization show better damping behaviors [106]. Unlike GFL, grid-forming inverters inherently synchronize with the grid through power-angle control. However, these strong interactions between the grid and GFM converters complicate the dynamics of the power system, resulting in oscillation and poor damping [107]. A small-signal impedance scan over a broad frequency range can be utilized to assess the oscillation-damping characteristics of grid-forming converters [108].

4.1.5. Sink for harmonics

In the traditional power systems, the rotor and stator reactance of the synchronous generators provide a natural path (sink) for damping harmonic and inter-harmonic components. However, in weak grids, due to the absence of synchronous generators, the system may lack 'sinks' to lower- order harmonics. *Therefore, GFM inverters should be capable of mitigating voltage harmonics at the point of connection by providing a current path for non-fundamental frequencies up to a limit of* 2kHz *(ENTSO-E)*. Furthermore, according to AEMO, *a GFM inverter should be capable of providing a passive damping response in the harmonic frequency range*. GFM inverters can change their impedance or damping profile by dynamically adjusting the control response within the harmonic frequency ranges. Unlike synchronous generators, which exhibit purely inductive impedance characteristics, grid-forming (GFM) inverters can offer superior harmonic performance due to their ability to present inductive or resistive-inductive impedance profiles [109]. The grid-forming inverter is required to be overrated or operate below its rated capacity (headroom) to act as a sink for harmonics and support stability (AEMO).

Various selective harmonic-compensation techniques for grid-forming converters in weak-grid conditions are proposed in the literature [110,111]. Active harmonic Filtering can significantly reduce total harmonic distortion (THD) at the point of interconnection (POI), but it may push the converters into overcurrent conditions. To overcome these current limitation conditions, a selective current limitation mechanism that dynamically adjusts virtual harmonic impedance based on the converter's loading conditions is proposed in Ref. [112]. The study in Ref. [113] outlines the development and implementation of GFM inverters in the UK power grid.The report highlights the need for harmonic control across a broad frequency range and discourages the injection of even or inter-harmonics, which could interact adversely with legacy grid filters.

4.1.6. Sink for unbalance

According to NERC, to support voltage balancing under weak grid conditions, *GFM inverters are required to supply negative phase sequence (NPS) current within their total current and NPS capability limits.* If large amount of negative sequence current impose additional stress on the equipment, a reduction in current magnitude is allowed after discussions with the related system operators. Furthermore, according to AEMO, *the voltage-source behavior of the GFM inverters should act to mitigate voltage unbalance caused by disturbances such as asymmetrical faults or unbalance loading.* This could be achieved by emulating a balanced voltage source that naturally injects positive and negative-sequence currents based on the nature of the voltage disturbance. According to ANSI C84.1, in power systems voltage imbalance must be less than 3 %.

To reduce voltage imbalance, control response can be dynamically adjusted to accurately tune negative-sequence impedances. Proper tuning of these impedances allows the GFM converter to directly inject required negative-sequence currents. The analysis in Ref. [114] shows that the negative sequence current injection capability of GFM inverters is limited to 57.7 % due to the rated current limitations. Grid-forming inverters (GFIs) demonstrate strong capabilities to address voltage unbalance in power systems, particularly under unbalanced load conditions common in distribution grids [115,116]. The analysis in Ref. [117] uses phase-balancing feedback-based droop control mechanisms to reduce the voltage unbalance factor (VUF) to less than 2 % across transmission and distribution systems. Table 8 summarizes GC requirements for the discussed GFM specifications.

Table 8
Summary of grid code requirements for GFM functional specifications.

Requirements	AEMO	ENTSO-E	GC 0137(GB)
Voltage Source Behavior	• Voltage source behavior within current capability limits	• Operate as a voltage source behind impedance during normal operation and fault conditions	• Voltage source behavior over a frequency range of 5 Hz to 1 kHz between, during and after fault
Voltage magnitude step	• Near instantaneous power response to oppose change in voltage magnitude	• Near instantaneous power response to oppose change in voltage magnitude	• Near instantaneous (less than 5 ms) power response to oppose change in voltage magnitude
Voltage angle step	• Near instantaneous response to oppose voltage angle change	• Near instantaneous response to oppose voltage angle change	• Near instantaneous response • Capability to withstand large voltage angle changes of:200° for 5 ms 90° for 60 ms
Inertial response	• Inherent inertial response i.e. no calculation of frequency and ROCOF • Wider range for inertia constant i.e. 2-9 s	• Inherent inertial response • Non exhaustive requirement for type B, C and D	• RoCoF withstand capability up to 2 Hz/s over rolling window of 500 ms • Inertial response up to a RoCoF of 2 Hz/s
Fault current injection	• Inherent fast fault current injection	• Fast fault current injection • Delayed fault current injection (up to 20 ms), under current limiting condition	• Fast fault current delivery within 5 ms–30 ms • Operation at minimum short circuit level of 0 MVA
Oscillation Damping	• Impedance phase angle between +90 and −90° at frequencies from 10 Hz to 500 Hz	• Limited controller bandwidth • Impedance phase angle difference less than 180°	• Damping factor between 0.2 and 5 • Controller bandwidth below 5Hz
Sink for Harmonics	• Power quality requirements	• Path for non-fundamental frequencies up to 2 kHz	• Passive damping response in harmonic frequency ranges
Sink for unbalance	• Power quality requirements	• Inject negative/positive sequence current	• Natural injection of negative/positive sequence current

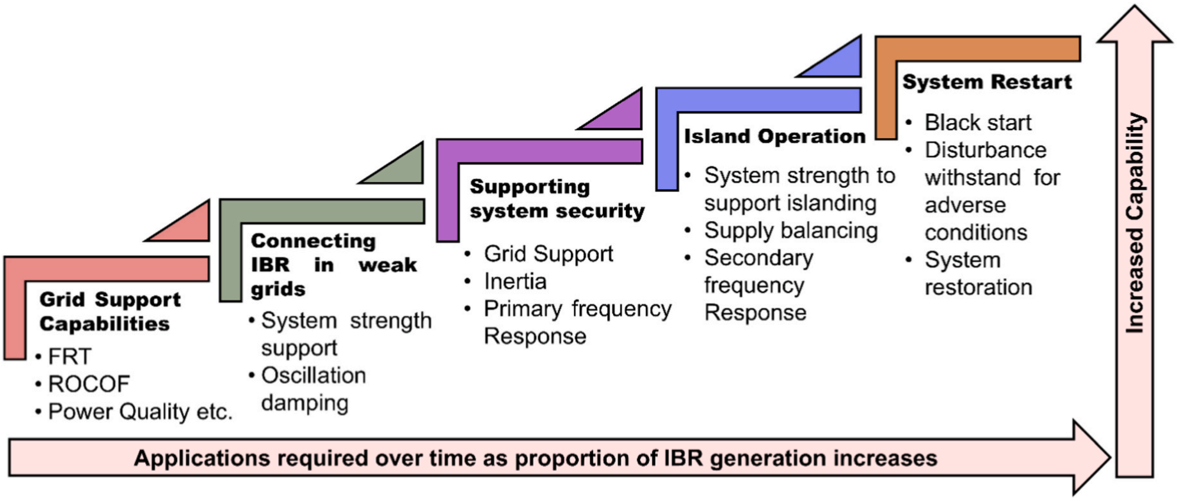

Fig. 7. Advance grid-forming capabilities [120].

4.1.7. *Advance GFM capabilities*

In the future renewable-dominant grids with fewer synchronous generators (SGs), advanced GFM capabilities will play an important role in enhancing resilience and stability. These capabilities, as illustrated in Fig. 7, include black start support, island operation, and the provision of primary and secondary frequency response, among others. *GFM inverters should possess the additional ability to initiate or* support *black-start procedures when necessary. An overload capability, i.e., the ability to operate temporarily above the rated current, is essential for system restoration (AEMO and NERC).* Various PHIL and EMT simulation studies have been conducted to assess the black start capability of GFM converters [118,119]. Moreover, GFM inverters should be capable of maintaining stable operation during system splits and the loss of the last synchronous machine events (AEMO, Fingrid, NERC).

4.2. *Compliance testing framework for GFM IBRs*

The current EU regulation, NC RfG 1.0, does not provide specific compliance testing procedures or guidelines for GFM converters. Existing compliance rules outlined in Articles 40–43 of NC RfG 1.0 can be used to assess certain grid-support capabilities like frequency support, voltage response, flicker, harmonics, and fault ride-through. However, capabilities such as synthetic inertia, oscillation damping, operation at current limits, and islanding, which are unique to grid-forming behavior, require more specialized testing procedures.

The concept of grid forming adds an additional layer of complexity to the performance validation process, both at the simulation level and during physical testing. An important consideration during GFM compliance verification is whether the inverter is operating in normal or current limiting conditions. The low maturity level of GFM converters and their unique behavior highlight the need for benchmark systems with clearly defined test cases. Simulation-based test frameworks for verifying core grid-forming capabilities have been proposed in various grid code-related reports and standards [83,121,122].

To evaluate grid-forming behavior, ENTSO-E has defined certain tests that simulate real-world grid disturbances. These tests, summarized in Table 9, are technology-neutral meaning that various control techniques and inverter types can be evaluated using a common benchmark. A simplified Thevenin equivalent network with controllable grid voltage and impedance is used as the benchmark system for testing. Using these tests, GFM behavior can be validated through either time-domain simulation or HIL-based testing. These tests assess core grid-forming capabilities, such as operating as a voltage source behind an impedance, responding in a controlled and stable manner, maintaining sustained voltage and frequency stability, and ensuring stable operation during faults and islanding conditions.

Table 9
Summary of verification tests for grid-forming capabilities.

Test	Event/Purpose	Expected Behavior	Compliance Criteria
Voltage angle step	• ± 5-degree voltage angle step at SCR of 10 (recommended)	• Instantaneous active current injection/ absorption in response	• Rise time ≤10 ms • Settling time ≤60 ms • Operator may define compliance criteria at a project specific level
Voltage magnitude step	• Small amplitude change (no current limiting)	• Instantaneous reactive power injection/ absorption	• Stable response and oscillation damping
SCR steps	• Verify dynamic performance by changing grid strength • Change grid strength by varying SCR	• Maintain stability under weak grid scenarios	• Damping current and voltage oscillations • Stable control
Loss of last synchronous generator	• 100 % IBR scenario • Islanded Operation	• Regulate voltage and frequency without tripping	• Stable voltage between 0.9 and 1.1p. u • Stable frequency
ROCOF	• Rapid frequency change 2 Hz for 0.75 s 0.5 Hz for 3 s	• Instant active power response (synthetic inertia)	• Rise time ≤10 ms • Settling time ≤60 ms • TR ≤ 25 s • Stable operation
Symmetrical voltage step (large)	• Verifying current limiting under fault • Large voltage drop while DUT operate near current limits	• Inverter limits the current and help grid	• Reactive current response during faults • Post fault damping
Unbalance voltage step	• 2 phase asymmetrical fault	• Efficient handling of negative and positive sequence current • No power imbalance	• No tripping • Quick voltage recovery
ROCOF + Voltage angle step	• Blackout event • Fast load changes	• Inverter should react smoothly and stay synchronized	• Same as voltage angle step + ROCOF compliance criteria

4.3. *Open research questions on GFM integration*

This subsection addresses various open research questions related to GFM integration, by drawing insights from recent technical reports, white papers, and grid codes.

4.3.1. *Grid forming capability optional or mandatory requirement*

Prior studies show that stability issues usually arise when the volume of IBR exceeds 65 % of total generation. This suggests that GFM capability is not required from all generating plants at all times. This naturally raises the question: should GFM capability be mandatory for all new plants, or should a market-based approach, with selected plants offering GFM capability under contract or incentives, be used? Making GFM capability mandatory increases the developer cost but results in enhanced resilience and operational flexibility of the power system. Similarly, making grid-forming capability optional results in low cost but reduces operational flexibility and resilience of the grid.

The additional costs associated with GFM technology presents a substantial barrier in its rapid deployment. These costs include infrastructure (hardware, control/firmware, component update), operational (headroom/oversizing) and compliance (EMT studies, compliance verification and commissioning tests). Furthermore, the risks associated with adopting new technology may influence the cost of the project. Despite these upfront costs, the revenue potential for adopting GFM technology is substantial through premium pricing and ancillary service payments. With increasing demand for stability services, GFM capabilities such as inertia, system strength, frequency and voltage support etc. are recognized as valuable. As the system operators move from experiments to procurement, GFM resources (especially BESS) with capability to provide grid strength services becomes a product with clear buyer value [123,124].

Furthermore, by adopting GFM technology earlier, developers get competitive advantage in growing grid stability market gaining competitive edge. In GB, National Grid ESOs stability path finder has created a real market for stability services. Under stability path finder phase 2 tenders' National grid ESO has awarded ten contracts worth 223 million pounds to grid stability projects in Scotland. These 10 contracts has been awarded to two technologies (5 synchronous condensers and 5 GFM BEES) to secure 11.55 GVA of short circuit levels and 6.75 GVA seconds of inertia [125,126]. Also in Australia, very fast raise/lower fast frequency control ancillary services (FCAS) markets were introduced in 2023 [127]. According to Australian energy regulator report [128], BESS with GFM capability are anticipated to be a dominant player in providing these ancillary services capturing majority of the FCAS revenues.

The debate of making GFM capability mandatory or market driven also involve important economic trade-offs. Mandating GFM technology could increase upfronts costs for developers as GFM are more expensive than GFL due to advanced operational, compliance and infrastructure requirements. However, mandating GFM offer long term grid resilience and stability benefits such as voltage regulation, frequency support, synthetic inertia, system strength support and black start etc. It is also worth noting that cost of incorporating GFM technology (especially GFM BEES) is lower than other alternative solutions such as STATCOMS, synchronous condensers, must-run thermal units, renewable curtailment and infrastructure updates. Therefore, mandating GFM would ensure resilience and stability of modern grids and make them more affordable by providing long-term cost savings.

On the other hand, in market-driven mechanisms developers are not required to adopt GFM technology if it is not needed, allowing them to opt for less expensive alternatives such as GFL or use existing infrastructure. This mechanism reduces initial capital costs and investment risks associated with the new technology. However, market driven mechanism may lead to slow widespread adoption of GFM technology. This slow integration could compromise grid resilience and stability, particularly in regions with high renewable penetration. Moreover, in the absence of clear requirements and incentives, grids continue to rely on synchronous condensers or thermal plants for grid stability, which are less flexible and more expensive in long run compared to GFM inverters.

ENTSO-E perspective is that GFM capability should be a mandatory requirement for new power plants. Grid codes such as GB 2022 consider GF capability as a mandatory requirement. According to NREL "*Installing GFM today will help avoid the costs of installing large additional grid*-supporting *devices or grid reinforcements in the future*". ESIG perspective is "*Least-cost grid stability solutions are not just an opportunity; they are a necessity*". Finally, NC RfG 2.0 clearly answer this question by including GF capability as a mandatory requirement for type B, C, and D power plants. The general conclusion is that providing some sort of GF capability is mandatory for future generating units.

4.3.2. *What is minimum required GFM penetration?*

It is well understood that GFM inverters will be necessary to stabilize the grid in future inverter-dominant power systems. Naturally, this raises the question: what proportion (percentage value) of GFM-enabled IBRs is necessary or recommended to maintain system stability? While there is no rule-of-thumb to prescribe this threshold, recent studies give some valuable points of reference [129,130]. The study in Ref. [102] performs real-time PHIL simulations to identify the minimum required GFM capacity for stabilizing 240 MW Maui power system under various system inertia levels. The results show a non-linear relationship between system inertia and the required GFM capacity. In the case of strong grids, the system is stable without any GFM converter. In scenarios with low SCR (system strength), 12 % of GFM capacity was enough for grid stability. However, when system strength drops to nearly zero (100 % IBR), the required minimum GFM capacity to stabilize the grid increases linearly to 30 %. The authors of reference [102] recommend that GFM capacity requirements under various inertia or SCR scenarios should be added in the future grid codes.

The study in Ref. [131] developed a mathematical relationship between grid forming capacity ratio and generalized short circuit ratio to investigate how many GFM IBRs are required to ensure small signal stability in a power system. It was found that under various grid configurations 5–20 % of grid forming capacity is enough to stabilize the grid. A study during Migrate project [132], investigated various ratios of GFM and GFL converters in different power systems and concluded that grid following to grid forming ratio of approximately 37 % is enough for grid stability.

It is important to recognize that the required amount of GFM capacity should not be determined solely based on stability considerations; economic costs and operational constraints must also be considered. Therefore, rather than utilizing a fixed percentage of GFM, current research focuses on hybrid GFM/GFL control to balance stability and economic tradeoffs [133]. In hybrid control, inverters can operate in dual mode (GFL or GFM) depending on grid conditions. Under stable and strong grid conditions inverters operate in GFL mode. When grid become weak, unstable or experience disturbances inverter switches to GFM mode. However, the sudden switching from GFL to GFM or vice versa can cause large voltage or current fluctuations potentially leading to grid instability.

Therefore, efficient methods to achieve seamless switching between GFL and GFM modes under varying grid conditions are required [134]. The study in Ref. [135] proposed control system with multiple loops to achieve smooth switching between GFL and GFM modes, verifying the feasibility of hybrid GFM/GFL control. Similarly, the study in Ref. [136] proposed a software-defined grid framework that consider GFM mode as grid service that can be dynamically switched on or off. The authors designed an optimal scheduling framework to dynamically switch between GFM and GFL modes at every scheduling interval considering varying grid conditions. Case studies using modified IEEE 30 bus system verify the effectiveness of proposed methodology in achieving cost-effective operation and stability in grids with high renewable penetration.

Based on the above discussions, it can be concluded that the required GFM capacity is a dynamic and system-dependent variable, not a fixed number. The required GFM integration varies from one system to another and is influenced by factors such as renewable penetration level, grid configuration, grid strength (SCR), economic trade-offs and the specific contingency being analyzed. Furthermore, the required capacity also depends on the relative positions of the GFM and GFL converters within the network [137]. Therefore, optimal placement and proper sizing of grid-forming inverters can significantly reduce the total capacity needed for effective grid support [138,139]. The general conclusion is that there is no universally required percentage of GFM inverters; the optimal amount depends on stability needs and economic condition and is best determined through coordinated planning.

4.3.3. *Technologies for providing GFM capability*

Various technologies, such as Battery energy storage (BES), PV, wind, STATCOM, HVDC links, and synchronous condensers can provide grid-forming capabilities. A comparative analysis of these technologies, considering their suitability for core grid-forming applications like inertia support, oscillation damping, voltage control etc. is presented in Table 10 [140].

STATCOMs are better suited as complementary devices rather than primary GFM resources, due to their limited capabilities to provide inertia and active power support. In contrast, synchronous condensers are well-suited for GFM applications, offering high fault current contribution, inertia, damping, and effective voltage control. However, they have limited frequency support capability. Renewables (wind and PV) show limited GFM potential. In the case of renewables, most grid-forming capabilities can be achieved through significant reengineering of the control structure from active and reactive power provision to a frequency and voltage control-based design. Furthermore, capabilities such as phase jump and inertia provision are constrained by the limited inherent storage capacity. The storage capacity can be increased by using energy buffers, but this increases the overall cost of the system. Battery energy storage, with few inherent restrictions on active power reserves and inherent design compatibility with voltage &frequency control, is best suited for providing GFM capability. Various standards and working groups are actively defining requirements for GFM battery storage [141–143]. The current research trend is to use a hybrid approach based on existing, well-proven technology. The study in Ref. [144] utilizes a synchronous condenser (SC) for fault-current contribution and real inertia provision, alongside a battery energy storage system (BESS) for active power delivery and frequency support.

4.3.4. *Is GFM capability required at distribution level?*

The need for GFM capability at the transmission level is well recognized. However, its implementation as a mandatory requirement at the distribution level remains an open question. At present, the use of GFM resources in distribution networks is largely confined to microgrids operating in islanding modes [145–147]. However, with increasing penetration of DERs, the grid stability challenges, once primarily a concern at transmission level are now increasingly observed in distribution feeders. While connecting GFM BESS in transmission system can enhance bulk system stability, the study in Ref. [148] shows that relying solely on transmission level solutions is not always sufficient. Especially

Table 10
Comparative analysis of GFM technologies.

Technology	Inertia	Phase jump power	Frequency support	Fault current injection	Amplitude Jump power	Damping
Battery Storage	**High/Medium** (Synthetic inertia)	**High**	**High**	**Low** (1.1–1.5 times)	**High** (fast response)	**High** (natural response)
Synchronous condenser	**High** (real rotating inertia)	**High**	**No** (No real power source)	**High** (3–6 times)	**High** (slow response)	**High** (natural response)
STATCOM	**NO** (no active power)	**NO**	**NO**	**Low**	**High/Medium**	**High/Medium**
PV	**Low** (power curtailment, headroom)	**Low** (power curtailment, headroom)	**Low** (power curtailment, headroom)	**Low**	**Medium**	**Medium/Low**
Wind	**Low** (power curtailment, headroom)	**Low** (power curtailment, headroom)	**Low** (power curtailment, headroom)	**Low**	**Medium**	**Medium/Low**

when the electric distance between the transmission connected GFM resources and distribution network is large, the required GFM capacity at transmission level to stabilize the distribution grid grows significantly, often reaching levels that are technically or economically impractical. Therefore, strategic placement of GFM DERs at optimal locations in the distribution feeders can reduce the burden on the transmission resources and can improve the stability, power quality and hosting capacity of the distribution network.

However, the large-scale integration of GFM inverters into distribution networks may introduce significant safety and operational challenges, including unintended islanding, inadequate protection coordination, and the necessity for infrastructure upgrades [13]. Unintentional islanding and safety are the major risks unique to GFM integration at the distribution level. GFM are explicitly designed to maintain voltage and frequency even when separated from the grid. This characteristic increases the likelihood that unintentional islanding persists after faults [149]. This raises multiple safety and reliability risks, such as undetected earth faults, out of phase reclosing malfunctions of protection due to higher impedance and compromised services restoration [150,151].

Another challenge is the interaction with voltage regulation devices. Distribution grids typically use load tap changers, voltage regulators, capacitor banks, GFL with volt/var control to regulate voltage: same objective as GFM. Introducing GFM to this environment may result in voltage hunting, circular reactive power or even small-signal oscillations, if coordination strategies are not properly redesigned. Furthermore, protection and automation strategies need to be revised. Due to limited fault current contribution from GFM converters, conventional overcurrent, distance or directional relays may not operate properly [152].

Grid code perspective is that utilities currently lack standardized performance specifications for GFM DERs in distribution systems. Because of challenges discussed above, and immaturity of GFM standards, both NERL and expert group reports recommend limited penetration in MV/LV, and not making GFM mandatory at distribution level for now [153,154]. Moreover, the NC RfG 2.0 does not mandate GFM capabilities for low-capacity Type A generators. Also, FINGRID requires GFM functionality for IBRs with a capacity of 1 MW or more. Overall, the general conclusion is that currently there is no widespread mandate for GFM capability at the distribution level in grid codes. However, as medium-voltage (MV) and low-voltage (LV) microgrids with GFM battery energy storage systems (BESSs) become more widely adopted at the distribution level, grid code requirements for GFM IBRs in these networks must also evolve. Future grid codes should explicitly address the operational needs of intentional islanding and the integration of GFM IBRs in distribution systems. This includes the development of mutually compatible requirements for fault-ride-through, islanding detection, protection principles and settings, resynchronization etc.

5. Challenges and recommendations

This section discusses key challenges related to grid code compliance verification practices and GFM integration in modern power systems. Furthermore, recommendations and future directions are outlined for research, regulatory reforms and enhanced IBR integration.

5.1. Challenges related to compliance verification

In this subsection, key challenges and recommendations related to Compliance verification are discussed in detail.

5.1.1. Regulatory ambiguity in compliance framework

All modern grid codes mandate a binding framework for compliance verification, including operational notification procedures and ongoing monitoring. However, GCs do not specify standardized testing, model validation, or certification procedures, leaving room for divergent national approaches. This regulatory ambiguity has led to fragmented national practices and inconsistent compliance approaches, making it challenging for manufacturers to develop standardized solutions for multiple markets.

Recommendations: Establish a harmonized, stakeholder-driven compliance framework to align national testing approaches through standardized procedures, uniform acceptance criteria, and conformity templates. Existing standards such as EN 50549-10, UL 1741, IEEE P2800, IECRE OD-009, and IECRE OD-501 should be adopted as reference documents to support consistent and transparent grid code compliance at the regional level.

5.1.2. Modelling and validation challenges

GCs increasingly reinforce the role of simulation models as central to compliance testing, system planning, and impact assessment. However, the literature review reveals persistence inconsistencies in modelling and validation practices such as absence of standardized and transparent model exchange frameworks, numerical, and tool-specific discrepancies, fragmented validation practices and model aggregation challenges. These issues lead to inconsistent model formats, poor interoperability and unnecessary parameter tuning, ultimately limiting reproducibility, and confidence in model-based compliance.

Recommendations: To address these challenges, the following key recommendations are proposed.

- Establish a standardized validation framework aligned with IEC 61400-27-2 and IEC 61850 standards, defining clear validation steps, test cases, measurement requirements, and acceptance criteria.
- Develop a model validation repository (at least at the regional level) to ensure harmonized, transparent, and traceable model templates.
- Establish cross-platform benchmarking and co-simulation platforms to enhance model accuracy, neutrality, and scalability.
- Adopt advanced technologies such as digital twins to enable continuous validation, lifecycle tracking, and model calibration under evolving grid conditions.

5.1.3. Reasons for manufacturer non-compliance

Most inverter manufacturers do not intentionally ignore standards; rather, manufacturers' non-compliance arises from slow adaptation of internal processes, lack of standardized compliance procedures, and fragmented firmware management. Manufacturers face several challenges that contribute to non-compliance.

- *Lack of Harmonized GCs*: The lack of harmonized GCs forces manufacturers to customize control algorithms, firmware, and validation procedures to different national requirements. This significantly increases the cost and complexity of the compliance process.
- *Lagacy designs and outdated GCs*: GCs are evolving faster than the product life cycle. A large number of devices currently in operation were designed and validated based on outdated GC requirements. For example, according to Ref. [155], many inverters in Australia operate with obsolete AS/NZS 477.2:2015, instead of updated AS/NZ 477.2:2020 settings. Updating old devices to new GCs require firmware changes, hardware adjustments, and re-certification, resulting in higher cost and longer time to market.
- *Lack of standardized modelling and validation tools:* System operators demand simulation models before connection to verify the dynamic performance of grid-connected IBRs. However, this process is hindered due to the absence of standardized modelling tools, test procedures, and validation templates. Another important reason for non-compliance is the lack of standardized model exchange procedures between TSOs, DSOs and equipment makers. This lack of harmonized model-exchange procedures leads to fragmentation, making cross-project validation and benchmarking very difficult.
- *Economic Inefficiencies:* Economic and procedural burdens such as updating legacy stock to meet new GC requirements, duplicate

certification across countries, and repetitive testing fees prolong compliance validation timelines and impose financial strain on manufacturers.

Recommendations: To address these challenges, key recommendations include standardized testing and model validation procedures, development of transparent model exchange mechanisms, harmonized certification and documentation processes, a standardized modelling framework, and enhanced coordination among TSOs, RSOs, and manufacturers.

5.1.4. Limitations of grid code compliance methods

Grid code compliance can be demonstrated using physical tests, equipment certificates, validated simulation models, or HIL testing. Physical testing, though highly accurate, is expensive, time-consuming, and constrained by ambient conditions. While equipment certificates reduce costs, decrease time to market, and add neutrality to the compliance process, they remain limited to component level testing. Conversely, simulation-based testing offers benefits like low risks, high scalability, low costs and broader coverage but suffers from reduced fidelity and validation issues. Similarly, HIL though effective and promising, faces interface stability, latency, and synchronization challenges. Consequently, no single compliance method achieves the optimal balance between cost, accuracy, scalability, time-to-market, and neutrality. Therefore, none can be regarded as a universal solution for verifying all grid code requirements.

Recommendations: Adopt a hybrid compliance approach that combines all available testing methods i.e., on-site commissioning test for individual projects, component-level testing by independent certification bodies, and HIL and simulation-based testing during the design and connection phases.

5.2. Grid forming integration challenges

The initial modeling studies and real-world experience internationally have shown that GFM technology brings substantial benefits to networks in need of stability support. However, the adoption of GFM technology has been slower than experts have expected. The main challenges associated with slow GFM adoption are.

- *Regulatory and Standardization Gap:* GFM integration is facing a chicken-and -egg dilemma; manufacturers are hesitant to invest without regulatory clarity, while regulators are reluctant to specify requirements without field validations. Currently, GFM definitions and functional specifications regrading inertia, frequency support, voltage source behavior, system strength support, etc. vary across regions, creating confusion and limiting global adoption of GFM technology. Furthermore, GFM technology is still in the early stages of deployment with limited field demonstrations through pilot projects [156]. A major barrier to the uptake of advanced inverters at scale is their limited deployment and untested performance in large power systems.
- *Economic and market barriers:* The additional costs associated with GFM technology present a substantial barrier to its rapid deployment. These include upfront infrastructure, compliance, and operational costs, and may reflect the cost risk of adopting a design that is not yet well understood by the industry. Also, many GFM capabilities that can enhance grid stability are not yet fully valued or are not easily accessible as revenue streams. Although initiatives like stability path finder by national grid ESO and system strength assessment guidelines by AEMO [157] partially address this gap, most of the national and regional markets still lack a formal payment mechanism for GFM ancillary services.
- *Modelling and validation inconsistencies:* Capabilities such as synthetic inertia, oscillation damping, operation at current limits, and islanding support (unique to GFM behavior) require specialized testing procedures and modelling frameworks. However, existing grid codes do not provide specific modeling, validation, and compliance testing guidelines for these GFM capabilities. This absence of harmonized testing and model validation frameworks across manufacturers, utilities, and certification bodies poses a major challenge to large-scale GFM integrations.
- *Protection and coordination challenges:* The large-scale integration of GFM inverters into distribution networks may introduce significant safety and operational challenges, including unintended islanding, inadequate protection coordination, and the necessity for infrastructure upgrades. Furthermore, dynamic interactions between GFM converters and voltage regulation devices (OLTC, capacitor banks, etc.) can trigger small signal oscillations, voltage hunting, and circular reactive power flow issues.

Recommendations: The key recommendations and future research directions to address these challenges are.

- A harmonized and comprehensive set of GFM interconnection standards and functional requirements should be developed to enhance certainty among stakeholders. Furthermore, harmonized testing procedures, modelling and validation requirements, acceptance criteria, and confirmatory report templates for verifying compliance with unique GFM capabilities should be developed.
- Batteries are low-hanging fruit for GFM control implementation. Most, if not all, new bulk power system-connected BEES should be equipped with GFM technology [141].
- Regulators, system operators, and manufacturers should work together to develop clear policies, incentives, and revenue mechanisms for GFM stability and resilience services [158].
- High-quality, accurate, and useable GFM models for interconnection, grid planning and operational studies should be developed.
- Future research efforts, particularly focusing on advanced control methods, optimal placement methods, smooth GFL to GFM switching, GFM in black start applications, protection and coordination strategies, can help in accelerating GFM development and adoption.
- GFM technology should be first established and validated at transmission levels. When technology matures at the transmission level, large-scale adoption at the distribution level should proceed. Future grid codes should explicitly address the operational needs of intentional islanding and the integration of GFM IBRs in distribution systems. This includes the development of mutually compatible requirements for fault-ride-through, islanding detection, protection principles and settings, resynchronization, etc.

6. Conclusion

The motivation for this review stems from the continuous evolution of GCs, which are constantly updating to support the transformation of modern IBR dominant power systems. Grid code compliance remains a critical but complex aspect of IBR integration. While NC RfG provides a foundational regulatory framework, the absence of standardized testing and validation procedures has led to fragmented national practices, increasing the burden on manufacturers. High costs, procedural uncertainty, and inconsistent requirements hinder the development of scalable, compliant solutions. Moving forward, harmonized standards, validated simulation models, and HIL testing represent practical pathways to streamline compliance, enhance transparency, and support the efficient deployment of advanced inverter technologies.

Furthermore, this review examines the current landscape of grid code requirements, with a particular focus on standardized definitions, performance specifications, and testing frameworks relevant to grid-forming inverters. The study addresses various open research questions related to GFM integration, by drawing insights from recent technical reports, white papers, and grid codes. It discusses the role of GFM inverters in supporting low inertia grids, improving transient stability and enabling autonomous operation during 100 % IBR generation, islanding or black start scenarios. However, several key challenges remain including diverse interpretation of GC requirements across different regions and lack of universal compliance procedures for GFM converters. Furthermore, there are still many unresolved issues regarding optimal deployment strategies for GFM converters, especially in weak grids, where scalability, stability and interoperability remain open questions. Therefore, a coordinated effort among researchers, regulators and manufacturers is required to develop validated models, harmonized GC requirements, compliance procedures and optimal integration strategies for efficient deployment of GFM converters in the evolving power system.

CRediT authorship contribution statement

Muhammad Kamran Khan: Writing – original draft, Writing – review & editing, Visualization, conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation. **Kimmo Kauhaniemi:** Writing – review & editing, Visualization, Resources, Supervision, Project administration. **Hannu Laaksonen:** Writing – review & editing, Supervision. **Mustafa Alrayah Hassan:** Writing – review & editing, Project administration.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used ChatGPT in order improve readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of competing interest

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

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Data availability

No data was used for the research described in the article.

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