Global Gateway

Co-funded by the European Union

german cooperation
DEUTSCHE ZUSAMMENARBEIT

Implemented by
giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Review of International Best Practices and Standards for Grid-Forming Battery Energy Storage Systems

EU4SustainableCentralAsia: Renewable Energy in Central Asia (EURECA) Regional Project

Submitted by
Energynautics GmbH
Robert-Bosch-Straße 7
64293 Darmstadt, Germany
Phone: +49 6151 785 81 06

Authors
Daniel Masendorf, d.masendorf@energynautics.com, Energynautics GmbH

Reviewed by
Nis Martensen, n.martensen@energynautics.com, Energynautics GmbH
Lucija Rakocevic, l.rakocevic@energynautics.com, Energynautics GmbH

Version: 1.0
16 December 2025

This report was developed in the frame of the EU4SustainableCentralAsia: Renewable Energy in Central Asia (EURECA) Regional Project through a Leveraged Partnership with GET.transform. EURECA is commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ) and co-financed by the European Union (EU).

GET.transform is a technical assistance programme supporting national and regional partners and institutions in advancing their energy sector transformations. GET.transform is part of the European multi-donor platform Global Energy Transformation Programme (GET.pro), and supported by the European Union, Germany, Norway, the Netherlands, Sweden and Austria.

Under its *Leveraged Partnerships*, GET.transform lends its advisory services to other European-funded technical assistance projects implemented by GIZ. GET.transform thereby increases its reach and capacity to mainstream and scale-up power system transformation solutions. www.get-transform.eu

Table of Contents

List of Figures

List of Tables

1 Executive Summary

The increasing share of inverter-based resources (IBRs) and the retirement of synchronous generators reduce rotational inertia and system strength, challenging power system stability. Grid-forming (GFM) inverters are emerging as a key solution, capable of acting as a voltage source to stabilize the grid. This report analyses 11 different international guidelines from Australia, Europe, North America, and South America to provide recommendations for implementing GFM standards for Battery Energy Storage Systems (BESS) in Kazakhstan.

First an introduction to each of the guidelines is given, before the report compares different options for procurement of GFM capability (mandatory, voluntary or market).

In the next chapter the following GFM core capabilities for which there is an international consensus are described in detail:

- **Voltage Source Behaviour**: The inverter must maintain a constant internal voltage phasor in the subtransient time frame, allowing immediate response to grid changes.
- **Step Responses**: Inverters must provide an instantaneous reaction of currents (or within milliseconds) to voltage phase angle and magnitude steps.
- **Inertial Response**: GFM BESS must provide active power proportional to the Rate of Change of Frequency (RoCoF).
- **Weak Grid Operation**: The capability to operate in very weak grids and survive the loss of the last synchronous machine is essential.
- **Damping**: Active and reactive power outputs must be adequately damped following disturbances.

In addition to the definition of GFM requirements, it must also be specified how these capabilities are verified. Verification typically involves a combination of Electromagnetic Transient (EMT) simulations and measurements. The level of detail in the descriptions of verification procedures varies considerably between the different guidelines. The Australian and Texan frameworks are well structured and reasonably extensive. Consequently, they are described in more detail as a illustrative examples. The Australian guideline has even been adopted by other regions.

Based on the review, the following recommendations were developed for Kazakhstan:

- **Define Functional Requirements:** Specifications should focus on performance outcomes rather than specific control architectures. Requirements should be precise, using equations and specific numbers (e.g., settling times) to avoid ambiguity found in purely qualitative descriptions
- **Align with International Standards:** Adopting established international practices facilitates market competition and interoperability for manufacturers.
- **Comprehensive Verification:** Implement an exact testing protocol that includes both grid-connected and island mode tests, with clear success criteria for each test.

2 Introduction

2.1 Context and Background

The increasing share of inverter-based resources (IBRs) such as solar PV and wind power, coupled with the retirement of conventional synchronous generators, presents significant challenges to the stability and reliability of power systems. The reduction of rotational inertia and system strength and the interaction of weak grids with inverter control loops can lead to issues with frequency and voltage stability, making the grid more vulnerable to disturbances [1][10].

Grid-forming (GFM) inverters are emerging as a key technology to address these challenges. Unlike traditional grid-following (GFL) inverters that rely on a strong grid voltage reference, GFM inverters can create their own voltage reference, effectively acting as a voltage source. When applied to Battery Energy Storage Systems (BESS), GFM technology can provide a wide range of grid-stabilizing services [12].

2.2 Objective and Scope of the Report

The objective of this report is to provide a comprehensive analysis and overview of the international specifications and best practices for GFM BESS. Since the worldwide landscape for GFM changes quickly and frequently new guidelines are published, this report focuses on the most recent and most advanced documents. The guidelines listed in Table 2.1 have been considered.

Following the summary of international best practices, recommendations for Kazakhstan are provided. In order to integrate grid-forming inverters into the grid, the following questions should be answered:

- How to make battery projects use GFM inverters?
- Which requirements should GFM inverters meet?
- How should compliance with these requirements be verified?

The report provides a basis to enable KEGOC and the Kazakhstan government to adopt requirements for GFM BESS in line with international best practices..

Table 2.1: Overview of analysed documents

	COUNTRY/ REGION	GUIDELINE	PUBLISHED BY	DATE	DOCUMENT TYPE	NUMBER OF PAGES	LINK
[1]	Europe	Grid forming capability of power park modules - Report on technical requirements	ENTSO-E	03. October 2025	Non-binding proposal for implementation in national guidelines	79	https://eepublicdownloads.entsoe.eu/clean-documents/Publications/SOC/20251104_GRID_FORMING_CAPABILITY_OF_POWER_PARK_MODULES.pdf
[2] [3]	Australia	Voluntary Specification for Grid-forming Inverters, Core Requirements Test Framework	AEMO	May 2023, January 2024	Preliminary documents to provide guidance while the regulatory environment around grid-forming develops (currently in progress)	23 41	https://www.aemo.com.au/initiatives/major-programs/engineering-roadmap/engineering-roadmap-execution-reports
[4]	Chile	Requisitos Técnicos Mínimos para Recursos Basados en Inversores Grid-Forming	CEN	April 2025	Grid Code	39	https://www.coordinador.cl/wp-content/uploads/2025/04/2025.04.02-Requisitos-Minimos-para-IBR-GFM.pdf

	COUNTRY/ REGION	GUIDELINE	PUBLISHED BY	DATE	DOCUMENT TYPE	NUMBER OF PAGES	LINK
[5]	Germany	Technical requirements for grid-forming capabilities including provision of inertia	VDE FNN	May 2025	Grid Code	200	https://www.vde.com/resource/blob/2405504/54fbd6d8e4fff81736108d1c21119380/fnn-guideline---technical-requirements-for-grid-forming-capabilities--october-2025--data.pdf
[6] [7]	Great Britain	European Connection Conditions, European Compliance Process	National Grid	11. June 2025 19. May 2025	Grid Code	143 (5 about gridforming) 101 (5 about gridforming)	https://dcm.nationalenergyso.com/
[8]	Denmark	Krav Til Transmissionstilsluttede Energilageranlæg Med Grid Forming Kapabilitet	Energinet	14. November 2025	Draft Grid Code	12	https://energinet.dk/regler/el/horinger/horinger/horing-af-teknisk-forskrift-332-energilageranlaeg-med-grid-forming-kapabilitet-november-2025/
[9]	USA	MISO Grid-Forming Battery Energy Storage Capabilities, Performance, and Simulation Test Requirements Proposal	MISO	July 2024	Draft Whitepaper	45	https://cdn.misoenergy.org/20240723%20IPWG%20Item%2004b%20DRAFT%20GFM%20BESS%20Performance%20Requirements%20White paper%20(PAC-2024-2)_REDLINE639677.pdf

	COUNTRY/ REGION	GUIDELINE	PUBLISHED BY	DATE	DOCUMENT TYPE	NUMBER OF PAGES	LINK
[10]	USA	White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems	NERC	September 2023	Whitepaper	51	https://www.nerc.com/globalassets/our-work/reports/white-papers/white_paper_gfm_functional_specification.pdf
[11]	Finland	Grid Code Specifications for Grid Energy Storage Systems SJV2024	Fingrid	15. January 2025	Grid Code	93 (not all about grid-forming)	https://www.fingrid.fi/globalassets/dokumentit/fi/palvelut/kulutuksen-ja-tuotannon-liittaminen-kantaverkkoon/sjv2024---unofficial-english-translation.pdf
[12]	Global	UNIFI Specifications for Grid-Forming Inverter-Based Resources Version 2	UNIFI Consortium	21. March 2024	Technical Report	21	https://unificonsortium.org/work-products/#toc_Specifications_for_Gridforming__Inverterbased_Resources
[13]	Texas, USA	Advanced Grid Support Energy Storage Resource (AGS-ESR) - Functional Specification and Test Framework for the ERCOT Grid	ERCOT	September 2024	Grid Code	13	https://www.ercot.com/files/docs/2024/09/16/ERCOT%20Advanced%20Grid%20Support%20ESR%20Test%20Requirement_.pdf

3 Overview of International GFM Frameworks

3.1 Australia (AEMO)

The Australian Energy Market Operator (AEMO) has developed a "Voluntary Specification for Grid-forming Inverters". AEMO's approach is to define "core" capabilities that are expected to be achievable with minimal modifications to plant hardware and "additional" capabilities that may require more significant upgrades. AEMO emphasizes a performance-based approach, providing illustrative examples and expected performance for various grid scenarios. However, no quantitative requirements are given [2].

In addition, AEMO has published a related document, the “Core Requirements Test Framework” [3]. The test requirements use the NERC whitepaper as orientation [10], but adds more tests. The loss of the last synchronous machine is tested with four different load conditions. In addition, the reaction to changing frequency, angle steps and fault-ride-through with different short circuit ratios is tested. Finally an impedance scan is suggested. Clear success criteria are formulated, including quantitative requirements, which are missing in [2]. This AEMO document had a large influence and was copied to a large extent by Chile [4] and MISO [9] and to some extent by ERCOT [13].

Both Australian documents serve as guidance while the regulatory environment around GFM is being developed, which is currently in progress. Regardless, several grid forming projects have already been implemented in Australia.

3.2 Europe (ENTSO-E, FNN, Fingrid, Energinet, UK National Grid)

The requirement for IBRs to include GFM capability is expected to be included on European level in the upcoming revision of the European Grid Code “Requirements for Generators” (RFG 2.0) [14]. However, it is still in the consultation phase and hence has not been published yet. Consequently, some of the member countries have already published their own guidelines, which are analysed here. In addition, very recently, the European Network of Transmission System Operators for Electricity (ENTSO-E) has published a report on the technical specifications for GFM and the verification procedure. The following documents are considered here:

- **ENTSO-E**: ENTSO-E has published a detailed report on the "Grid Forming Capability of Power Park Modules"[1]. This report proposes a comprehensive set of technical requirements for GFM capabilities. It provides a non-binding proposal of detailing GFM technical requirements of the amended Network Code on Requirements for Generators (NC RfG) [14] in the national implementation, including compliance verification. It was developed in parallel with the German requirements [5] described below and some of the requirements in both documents are the same or very similar. It includes a detailed description of typical requirements such as voltage source behaviour and reaction to angle or magnitude steps. In contrast to most other documents, the effective impedance of the GFM IBR is handled in detail and maximum allowed impedances are specified. Another outstanding requirement is that the GFM capability is explicitly defined at the terminals of a power plant and not at the terminals of a generation unit.

- **VDE FNN (Germany)**: The German entity VDE FNN has published a guideline on "Technical requirements for grid-forming capabilities". The VDE FNN guideline is by far the most comprehensive of the analysed documents. It includes not only a detailed description of the GFM capabilities (with large overlaps with [1], but more extensive), but also very detailed chapters about verification and modelling aspects, providing specific requirements for EMT and Root-Mean-Square (RMS) models, as well as for model validation and documentation [5]. GFM is not mandatory, but certification according to this guideline is required to qualify for the upcoming inertia market in Germany (starting in the beginning of 2026). Since it is relevant for the market, the guideline emphasizes the provision of inertia more than most other documents.

  Besides the VDE FNN guideline, there are some separate documents regarding GFM from the German TSOs (not covered here).

- **Fingrid (Finland)**: Fingrid has incorporated the requirements for GFM in the general grid code for energy storage facilities: "Grid Code Specifications for Grid Energy Storage Systems SJV2024". Each battery with a rated power above 10 MW must be GFM. Core properties, such as voltage source behaviour and island operation are required. The description focuses on the functional requirements and few specific numbers are given. The GFM capability is verified through simulations in island mode, an impedance scan of the simulation models and measurements of voltage steps [11].

- **Energinet (Denmark)**: The Danish TSO, Energinet, is currently in the progress of defining requirements for GFM and has published a consultation version of its "Technical regulation for transmission-connected energy storage facilities with grid forming capability"[8]. This document is an amendment to the regular grid code for energy storage facilities. It specifies more detailed requirements than Fingrid. For verification, only simulations in island mode are required.

- **UK National Grid**: The UK's National Grid has incorporated GFM requirements into its “European Connection Conditions” through the "GB Grid Forming (GBGF) Capability". Only very few pages are dedicated to GFM requirements. Most requirements are high-level, but there is a detailed description of the reaction to voltage dips [6].

  Testing requirements are described in a separate part of the grid code, the “European Compliance Procedure”. Again there are 5 pages with description of different tests, such as reaction to changing frequency, phase steps and FRT. In contrast to most other documents, no tests in island mode are required [7].

3.3 North America (NERC, MISO, UNIFI, ERCOT)

- **NERC**: The North American Electric Reliability Corporation (NERC) has published a white paper on "Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems" (BPS = Bulk Power System). This paper defines GFM, discusses its benefits and recommends tests for verification. The focus is on functional requirements and no specific numbers or specifications for the transient behaviour are given. It is stressed that only validated models should be used for verification. For the verification, loss of last synchronous machine tests with three different load conditions are suggested. The paper is a recommendation for the North American system operators [10].
- **MISO**: The Midcontinent Independent System Operator (MISO) has published a "Grid-Forming Battery Energy Storage Capabilities, Performance, and Simulation Test Requirements Proposal". The document includes other aspects, such as a discussion of the industry landscape and a review of the process for developing the requirements. The GFM capabilities focus on the absolute core requirement, the operation as a voltage source including transient requirements for the dynamic response. In addition, the document includes requirements for modelling and proposes a set of simulation tests for demonstrating compliance. These tests are copied from Australia, but adapted to MISO’s preferences in certain details [9].
- **UNIFI**: The UNIFI Consortium, an initiative funded by the US Department of Energy, has developed "Specifications for Grid-Forming Inverter-Based Resources". These specifications aim to provide uniform technical requirements for GFM IBRs of any size and at any scale. UNIFI uses a different wording than the other documents. The term “voltage source” is not mentioned in the document. Instead, other requirements are given, such as “operation in grids with low system strength” and “autonomously support the grid”. All requirements are functional and no quantitative specifications are made. Requirements regarding verification are out of scope of this document [12].
- **ERCOT:** The “Advanced Grid Support Energy Storage Resource (AGS-ESR) - Functional Specification and Test Framework for the ERCOT Grid” from the Texan system operator ERCOT uses the term “Advanced Grid Support”, but it means the same like GFM in the other documents. There is no dedicated chapter on requirements, but the requirements are included in the performance criteria of the described tests. The described tests have a reasonable extent and the performance criteria are well defined, including functional and quantitative criteria, e.g. minimum currents, and dynamic requirements, e.g. within one cycle [13].

3.4 South America (CEN)

The Coordinador Eléctrico Nacional (CEN) of Chile has published "Requisitos Técnicos Mínimos para Recursos Basados en Inversores Grid-Forming" [4]. CEN's document proposes minimum functional technical requirements for GFM IBRs and a framework for testing via simulations, including different test benches. Quantitative requirements are not specified, but there are simulation results for the required tests included and it is mentioned that the results of a GFM should be similar or better than the shown results. In addition, success criteria are given, which include requirements for the dynamic response. The required tests are almost exactly copied from AEMO [3].

4 Procurement of Grid forming capability

In principle, for any need of the power system, there are three possibilities to ensure it is met:

- Grid codes make it mandatory for grid users to include the required capabilities.
- A market for the needed capabilities is created.
- The system operator installs their own assets to tackle the challenges.

In addition to the three possibilities listed above, there are also some guidelines with "voluntary requirements". In the case of Australia, it is seen that even with voluntary requirements GFM projects are implemented. This shows that it can be economically advantageous to implement GFM, e.g., if frequency reserves are provided with a battery instead of a gas power plant.

In the special case of GFM inverters, each of the three options is possible and used to some extent internationally. Table 4.1 gives an overview of the solution that was selected by the analysed countries. Some countries have not decided yet about the approach.

If GFM behaviour is made mandatory, it should only be required from BESS, since for renewable generators it is significantly more difficult. However, for renewables, it can be included as a voluntary requirement.

Table 4.1: Overview of approaches for upscaling GFM

AEMO (AU)	MISO (US)	UK Grid (UK)	Fingrid (FI)	Energinet (DK)	CEN (CL)	VDE FNN (GER)
Voluntary	Initial step on the pathway to deliver needed attributes by enabling GFM	Market approach	Mandatory for BESS >10 MW	Voluntary requirement, Amendment to normal grid code	Still to be decided if market or mandatory	Market for Inertia

5 GFM capabilities

This chapter provides insights into GFM requirements for IBRs. However, it is important to note that mandatory requirements should only be applied to BESS. For other IBRs, such as wind and PV, the technology is not yet that advanced and implies further restrictions, such as curtailed operation. Consequently, if GFM requirements are specified for wind or PV then they should be voluntary.

In the following chapter 5.1, the core capabilities of GFM inverters, as required in international best practices, are described. These capabilities are unique for GFM IBRs and are not requested from GFL IBRs. All GFM IBRs in the grid should have these capabilities.

Additional GFM requirements are listed in chapter 5.2. These requirements cannot be delivered without increased effort such as hardware upgrades. Consequently, they should not be requested generally, but only after separate discussion with the project developers.

Chapter 5.3 describes requirements for GFM IBRs that already exist for GFL IBRs but might need to be adapted for GFM IBRs.

All requirements only apply for operation within the ratings of the IBR. When the current limits are reached, the GFM IBR can still continue operating GFM by using current limiting techniques, such as virtual impedance or reducing the voltage setpoint. However, in this case the GFM requirements, such as inertia or phase angle power or reactive power with voltage magnitude steps cannot be fulfilled or only to a lesser extent. This should be kept in mind for the operation of the GFM IBR. The implications on the operation are usually not discussed in the guidelines.

When designing GFM requirements, it is recommended to align them with international best practices, since this will make it easier for the system operator to find suitable batteries and will make it easier for manufacturers to comply with the requirements.

5.1 Core GFM Capabilities and Main Requirements

5.1.1 Voltage Source Behaviour

The most fundamental characteristic of a GFM inverter is its operation as a voltage source. This requirement is stated in all guidelines. Representative for all documents, the specification from Australia is shown here [2]:

> "A grid-forming (GFM) inverter maintains a constant internal voltage phasor in a short time frame, with magnitude and frequency set locally by the inverter, thereby allowing immediate response to a change in the external grid."

In other documents, other wordings are used, but the content is the same or very similar. Some other requirements, such as the response to voltage angle steps or voltage magnitude steps are actually just a consequence of the voltage source behaviour. To shape the voltage source requirement better, details on the reaction to those events are provided in most grid codes.

Suggested approach:

Request voltage source behaviour and use a similar wording like above.

5.1.1.1 *Reaction to voltage phase angle steps*

Most documents only provide a functional requirement for the reaction of active current to phase jumps, which is the inherent response of mainly inductive devices. Mostly an instantaneous reaction or within a few milliseconds is required.

In the guidelines from ENTSO-E [1] and VDE FNN [5] the following formula is given for the calculation of the theoretical maximal active current depending on the angle jump:

$$\Delta_{iP,PGU,Peak} \approx -\frac{1}{x_{\mathrm{Eff}}}(sin(\delta + \gamma) - sin(\delta))$$

$\Delta i_{\mathrm{P,PGU,Peak}}$: expected theoretical peak
x_{Eff}: Effective impedance of GFM IBR, including hardware and virtual impedances in the control
δ: phase difference between the terminal voltage angle and the internal voltage of the GFM prior to the phase jump event.
γ: angle change applied by which the terminal voltage angle jumps from its steady-state value.

This reference value is used as a basis for a quantitative requirement. In both documents 50% of $\Delta i_{\mathrm{P,PGU,Peak}}$ are specified as minimum active current for each corresponding angle jump. In the Texan guideline, a minimum additional active current of 0.2 p.u. based on rated power is required for a 10 degree angle jump [13].

It is advantageous to define the desired behaviour through equation, since this definition is unambiguous.

Furthermore, maximum values for the effective impedance are specified. Depending on the voltage level, and if unit transformers are included, the maximum effective impedance is between 0.27 and 0.5 pu. The detailed discussion of the effective impedance is another unique feature of [1] and [5] not mentioned in the other guidelines, although it has a significant influence on the behaviour.

Suggested approach:

Request a minimum active current, depending on the voltage phase angle step, based on the formula above. In addition, specify maximum values for the effective impedance. For the dynamic behaviour, either specific times in milliseconds can be given or instantaneous reaction can be required.

5.1.1.2 Reaction to voltage magnitude steps

Similarly to the reaction to phase angle steps, a corresponding reaction of the reactive current to voltage magnitude steps is required in the guidelines. The reaction must happen instantaneous or within a few milliseconds. For this requirement, also the guidelines [1] and [5] are less precise and do not specify quantitative requirements. In the Texan guideline a reaction of 0.03 p.u. based on the rated power is required for a voltage step of 0.03 p.u. [13].

Suggested approach:

Request the functional behaviour for voltage magnitude steps. Potentially, require a minimum reactive current depending on the voltage step. For the dynamic behaviour, either specific times in milliseconds can be given or instantaneous reaction can be required.

5.1.2 Inertial and Frequency Response

The reaction to changing frequency with an inertial response is not described in all guidelines, but in most of them. It is as well an inherent effect of the voltage source behaviour with constant internal voltage phasor in subtransient time frame. The (synthetic) inertial response is an instantaneous active power response proportional to the Rate of Change of Frequency (RoCoF).

Although the initial reaction to changing frequency/ frequency steps is an inherent capability of the voltage source behaviour, it is worth to elaborate the requirements further, because the transient behaviour after the initial reaction can be shaped by the control equations. In theory, an arbitrary inertia can be emulated with GFM IBRs.

The most detailed guideline regarding inertia is the German one [5], since it is relevant for the upcoming inertia market. In this guideline as well as in [1] and [8] a start-up time constant T is used for the description of the inertial requirements. T is defined as the ratio between additional power due to changing frequency and the derivative of the frequency (all values in pu):

$$T = \frac{\Delta p}{\frac{\mathrm{d}f}{\mathrm{d}t}}$$

In all of the above mentioned guidelines $T = 25\mathrm{s}$ is mentioned as maximal value. With this inertia, 1pu active power is delivered during a RoCoF of 2Hz/s in a 50Hz system. Consequently, higher inertia constants would lead to active power requirements above the inverter rating with this RoCoF.

It is worth mentioning that this inertial power can only be provided if the GFM IBR has enough headroom or is capable of overloading for the relevant RoCoF [2]. The smaller the provided inertia, the less headroom is needed. Hence, the requirement for inertia comes with implications for the operation of the GFM BESS. However, in most documents this is not discussed. For Denmark [8] it is required that "The plant is designed and operated in such a way that it always has sufficient energy storage capacity to maintain the required change in active power […] for at least 5 seconds." In practice it is significantly more challenging to have the **required power** available than the required energy. In Germany, BESS are incentivized to operate with the required headroom, because they will not get remunerated for inertia if the needed headroom is not available.

Suggested approach:

Request inertia and specify a minimum start-up time constant or give a possible range. In addition, define operational constraints, i.e., for which duration and which RoCoF the defined inertia must be delivered.

5.1.3 Damping

The output of a GFM IBR following a disturbance should be damped adequately [5][10][2]. This contradictive to the requirement of a very fast and preferably large response to the disturbance, as described in 5.1.1.1. Consequently, tuning of the control for events, such as voltage phase angle steps is a trade-off between a fast and large response and a damped response.

Most guidelines mention damping in the requirements. Positive damping is required for a large range of frequencies. Some guidelines give simple functional requirement [4], while some documents specify certain frequencies, in which damping is crucial [11] and others define specific values for the damping factor of responses of the GFM inverter. In Great Britain the damping factor must be between 0.2 and

5 [6]. In Germany the damping for power frequency oscillations (which also includes the response to phase angle steps) must be above 0.5 [5].

Suggested approach:

Request a damped output of active and reactive power of the GFM IBR following disturbances. Possibly define specific values for the damping factor. In addition require damping of voltage and frequency oscillations of the grid and mention focused frequencies, if applicable.

5.1.4 Weak grid operation and operation without synchronous machines

A fundamental difference of GFM and GFL inverters is that GFM inverters are able to operate in very weak grids, even without synchronous machines. This is required in all guidelines but often different wordings are used. Great Britain requests operation at a short circuit level of zero MVA [6], Denmark requires the capability to operate in autonomous island mode [8] and NERC species the capability to stably operate following the disconnection of the last synchronous machine. In some guidelines, e.g., Australia, the requirement for a smooth transition without interrupted operation between grid connected and island mode and vice versa is highlighted [2].

Suggested approach:

Request operation without synchronous machines or use a different appropriate wording. Mention that the GFM should not be disconnected when transitioning between grid connected and island mode.

5.2 Additional GFM Capabilities and Requirements

5.2.1 Black Start Capability

Although GFM is a prerequisite for black start capability of inverters, a GFM inverter is not necessarily capable of black start, because black start capability imposes further requirements to inverters, such as overcurrent capability or requirements regarding stored energy. Consequently, black start capability is not required mandatory by any of the analysed grid codes. It should be agreed upon separately with the grid operator [10].

Suggested approach:

Request black start capability only in selected cases and discuss the details project specific.

5.2.2 Power Quality Improvement

GFM BESS can contribute to improving power quality by providing harmonic damping and reducing voltage unbalance due to their inherent voltage source behaviour [4][12]. Additional, active reduction of harmonics should not be required from GFM IBRs, because resulting harmonic currents might lead to a reduction of the fundamental current when operating near the current limit. Consequently, this capability is seen as an additional requirement in Chile and Australia and by the UNIFI consortium [4][2][12]. In Australia, this also applies damping of unbalances and flickers.

Suggested approach:

Rely on the inherent damping behaviour of a GFM. Only request additional mitigation of power quality in special cases if it is relevant for the considered part of the Kazakh system.

5.3 GFL requirements that might need adaption for GFM

Already GFL IBRs are required to support grid stability in different ways, such as through limited frequency sensitive mode (LFSM), fault ride through capability, different quasi-stationary reactive power control modes and others. These requirements are still relevant for GFM IBRs. However, in some cases they might need to be adapted or extended to the properties of GFM controls. The FRT-requirement is a good example, which is described here.

If other requirements for GFL need to be adapted or extended for GFM, also depends on how elaborated these requirements are already.

5.3.1 Fault-Ride-Through (FRT)

Most frameworks mandate that GFM BESS must ride through grid faults, i.e., they need to stay connected to the grid. The Australian guideline and MISO do not mention FRT capability in the requirements, but for the verification of GFM behaviour voltage dip tests are specified [2][9]. For this requirement the same FRT envelopes (curves that assign a minimum ride through duration to each voltage level of a voltage dip or voltage swell) like for GFL inverters can be applied.

However, the behaviour during the faults can be different from the behaviour of GFL IBRs. In Great Britain and Denmark an additional reactive current, proportional to the voltage dip shall be injected during the fault [6][8]. In other guidelines, no additional requirements are specified or it is stated that the GFM IBR must continue operating as a voltage source [11][4].

In the European, Danish and German requirements, it is specified that no current component (reactive or active current) should be prioritised. Instead, the magnitude of the current should be limited and the priority is to continue operating as a voltage source. Current clipping is only allowed for maximally 40 ms. The requirement for no prioritisation differs from typical requirements for GFL IBRs, which often prioritise reactive current over active current [1][5][8].

Suggested approach:

Request FRT capability from GFM IBRs. Specify that the priority of the IBR is to continue operation as voltage source. If desired, specify a prioritisation of current components or magnitude depending on the needs of the Kazakh system

6 Verification of Grid-Forming Capabilities

Similar to any other grid code compliance testing, different approaches are possible to assess the grid code compliance:

- Laboratory measurements
- Hardware in the Loop testing
- Field tests
- Simulation

With certain constraints, all of the above listed methods are applicable for proving compliance with the requirements. A FRT test is hardly feasible at a large power plant in the grid, so this should be done with a small unit in the laboratory or via simulations.

In the Chilean, Australian and MISO guidelines almost the same set of tests is required and it is specified that they should be done via simulations with an EMT model [3][4][9]. In the NERC whitepaper, which lays the foundation for the verification of these grid codes, it is stressed that only validated models should be used for the simulation [10]. This is a general requirement, which is true for all simulation models which are used for any proof of grid code compliance, because otherwise the simulation results are not reliable. This implies that measurements are needed, with which the simulation model can be compared for validation. It has to be specified, which measurements should be used for validation and which deviations between simulation and measurement are still acceptable. However, the approach of validating simulation models and certifying generation units can be quite laborious. From the analysed documents, it is only specified in the German guidelines [5]. This is one of the reasons, why this document is significantly longer than the others. However, due to the large effort and large extent of guidelines, the German approach is not necessarily the best approach. Anyway, the discussion of model validation is a general topic, which is not only relevant for GFM inverters but for all generators, so it is out of scope of the specific requirements for GFM which are the content of this document.

Not all guidelines give specifications for the simulation models. The guidelines who specify the model all request an EMT model. Some of them require an additional RMS model, e.g., Germany and Finland [5][11]. These guidelines also have in common that they both require measurements as well as simulations. In Germany 5 tests in island mode and around 40 tests in grid connected mode are required and all tests have to be done in measurement as well as in simulations (they are also used for model validation). In Finland some tests, such as island mode or reaction to phase angle steps are required via simulation, while the reaction to voltage steps is measured during commissioning.

When defining a set of tests or simulation for compliance checking, the following information should be included:

- Exact description of the test to be conducted, including
    - Description of the test setup
    - The operation point of the tested unit (active and reactive power and voltage) before the event
    - Description of the event(s) to be applied
- Succes criteria for passing the compliance check

Each of the specified requirements (see chapter 5) should be checked in a test. Potentially, the requirements should be checked multiple times under different conditions, for example with different dispatches, with reaching the current limit or without, with different short circuit power of the external grid. Just like the test cases, the success criteria have to be tailored specifically to the requirements for the GFM IBRs. Quantitative and dynamic success criteria should be added if such requirements are formulated.

An exact set of tests including evaluation criteria for Kazakhstan cannot be specified here, because it depends on the required capabilities, which are not yet selected. Some of the analysed guidelines, e.g. the German ones, are too extensive while others lack details, e.g., the Danish guidelines. In contrast to that the Australian and Texan frameworks are well-structured, detailed enough and reasonably extensive. Hence, they are described in the following as illustrative examples. Another exemplary set of tests is included in the European guidelines by ENTSO-E [1].

6.1 Australian Example

The Australian test seems to be useful, since it has been copied by Childe and MISO and hence can provide orientation when developing a set of tests. It uses the test benches shown in Figure 6-1 and the tests listed in Table 6.1 [3]. It builds upon the NERC whitepaper and extends the tests described there [10].

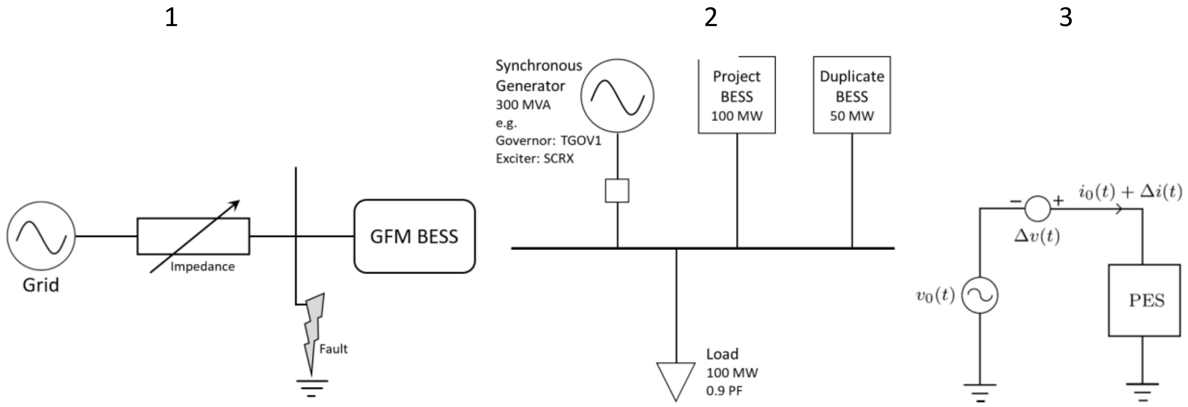

Figure 6-1: Used testbenches for simulations in Australia, 1: Single Machine Variable Impedance (SMVI), 2: Simplified network with load (SNWL), 3: Perturbed voltage source (PVS)

Table 6.1: List of tests for Australia

Test Nr.	Test Name	Testing for	Core Function Reference	Testbench System
1	Loss of synchronous machine – discharging	GFMI basic functions (BESS only)	Voltage Source Behaviour, Inertial Response, Loss of Last Synchronous Machine, Weak Grid and System Strength Support, Oscillation Damping	2 - SNWL
2	Loss of synchronous machine – charging	GFMI basic functions (BESS only)	Voltage Source Behaviour, Inertial Response, Loss of Last Synchronous Machine, Weak Grid and System Strength Support, Oscillation Damping	2 - SNWL

Test Nr.	Test Name	Testing for	Core Function Reference	Testbench System
3	Loss of synchronous machine – limits	GFMI basic functions, limits (BESS only)	Voltage Source Behaviour, Inertial Response, Loss of Last Synchronous Machine, Weak Grid and System Strength Support, Oscillation Damping	2 - SNWL
4	Loss of synchronous machine – power balance	GFMI basic functions	Voltage Source Behaviour, Inertial Response, Loss of Last Synchronous Machine, Weak Grid and System Strength Support, Oscillation Damping	2 - SNWL
5	RoCoF up and down	Control stability	Inertial Response, Weak Grid and System Strength Support	1 - SMVI
6	SCR ramp down with fault	Control stability	Voltage Source Behaviour, Inertial Response, Weak Grid and System Strength Support, Oscillation Damping	1 - SMVI
7	Angle step change	GFMI basic functions	Voltage Source Behaviour, Inertial Response, Weak Grid and System Strength Support, Oscillation Damping	1 - SMVI
8	Impedance scan - Informational	Damping, impedance trend and system strength support	Frequency Domain Response, Oscillation Damping	3 - PVS

The evaluation criteria are for example for the post-event behaviour of test 1:

- Immediately following the trip, plant output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady state levels for any significant amount of time.
- Voltage settles to a stable operating point.
- The final voltage is as expected based on the droop and deadband settings.
- Frequency settles to a stable operating point.
- The final frequency is as expected based on the droop and deadband settings.
- Any oscillation shall be adequately damped.
- Any distortion observed in phase quantities should dissipate over time.

- Active power from each plant should move immediately to meet the load requirement and settle according to its frequency droop setting. Note that response time to 90% of initial change in instantaneous active power should occur within 50ms.
- Reactive power from each plant should move immediately and settle according to its voltage droop setting.
- Voltage does not deviate beyond [0.8, 1.1] pu for longer than 0.1s throughout the test. These voltage bounds and the time threshold are based on preliminary testing, may be adjusted as more experience with this requirement is gained.

For other tests, of course different success criteria apply. Criteria for quantitative and dynamic requirements are given for some tests, e.g. active current following an angle jump. Some of the listed criteria are very specific for the Australian guideline, such as the response time and the requirement for voltage deviation.

6.2 Texan Example

ERCOT notably orientates on Australia and uses two of the three Australian test benches [13][3]. The document structure is as well very similar to the one from Australia and NERC [10]. However, ERCOT does not focus as much on the loss of the last synchronous machine, but instead adds an additional test for checking the model (flat start) and a test for small voltage disturbances. Some of the success criteria are extended, e.g. a minimum inertia requirement is added to the frequency change test, while other success criteria are simplified, such as the ones for loss of synchronous machine tests. The used test benches are shown in Figure 6-2 and a list of tests is shown in Table 6.2.

ERCOT emphasises the need for model validation and refers to another document with a description of tests for this purpose.

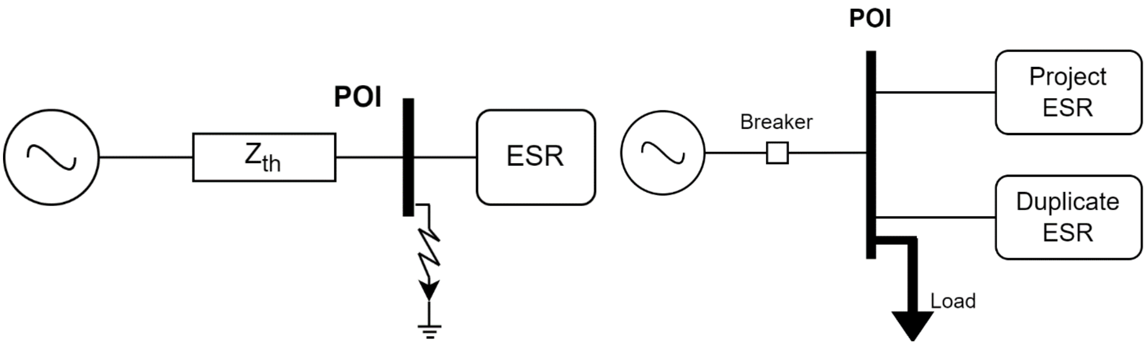

Figure 6-2: Used testbenches for simulations in Texas, left: Testbench 1, single-machine variable impedance system, right: Testbench 2, simplified network with load

Table 6.2: List of tests for Texas

Test Nr.	Test Name	Testbench System	Applicable Software
1	Flat start	TB1	PSCAD, PSS/E, TSAT
2	Phase angle jump	TB1	PSCAD
3	Small voltage disturbance	TB1	PSCAD, PSS/E, TSAT
4	Frequency change and inertia response	TB1	PSCAD, PSS/E, TSAT
5	System strength	TB1	PSCAD, PSS/E, TSAT
6	Large voltage disturbance	TB1	PSCAD, PSS/E, TSAT
7	Loss of synchronous machine	TB2	PSCAD, PSS/E, TSAT

As example, the success criteria for test 7 (similar to the Australian test 1) are listed below:

- Immediately following the disconnection of voltage source, both plants' output should be well controlled. System frequency and voltage should settle to a stable operating point (within 5 seconds) and not oscillate excessively and damped within 10 seconds or deviate from steady state levels.
- Active and reactive power from each plant should move immediately to meet the load requirement, while response time to 90% of initial change should occur within one cycle.
- Active and reactive power from each plant should move immediately and settle according to its droop setting.

7 Conclusion and Recommendations

The literature review has shown a clear, worldwide trend towards adopting the critical GFM technology. It has been observed that some requirements (such as voltage source behaviour, instantaneous reaction to voltage changes) are similar in almost all documents. Other requirements such as requirements regarding power quality or damping are handled differently in different guidelines. The verification of GFM capability is handled in the documents with a different level of detail as well. Further differences have been observed in the method for procurement of the GFM capability. The review provides a profound basis for recommendations regarding the different aspects of guidelines for GFM:

Procurement of GFM capability

So far voluntary requirements and market approaches are more common than mandatory requirements. However, having GFM requirements at all, is still rather new in the industry. It is conceivable that more mandatory requirements will come up when the GFM technology is better established in the market. The upcoming revision of the European grid code will most likely enable system operators to make GFM mandatory for certain asset [14].

Functional/ performance-based requirements

When drafting requirements for grid codes, it is crucial to **specify functional requirements**. It should be described how the response of an asset to a predefined event should look like. No requirements for control architecture or for a certain GFM type (e.g., virtual synchronous machine) should be made. It is the responsibility of the manufacturers to develop a solution that fits the specified requirements.

The level of detail in the specifications varies significantly. Some of the analysed grid codes merely have **qualitative requirements** (e.g., “reaction of active power to angle steps”). This can lead to different interpretations to which extent the required capability should be delivered. To ensure the same understanding, a **quantitative requirement** can be added (e.g., “provision of at least X p.u. active current for an angle step of Y degrees). The third possible level of detail is a **dynamic requirement** (e.g., “reaction in less than X ms and settling time less than Y ms”). The usage of equations and figures is recommended, to ensure unambiguous requirements and easy understanding.

Most analysed grid codes do not specify this level of detail for each of the requirements. Sometimes unprecise wordings, such as “near instantaneous” are used. Unprecise requirements could lead to undesirable behaviour, but it is not certain that this will happen. It can also simply leave more freedom for the manufacturers. It is appropriate to omit some details in requirements that have not the highest priority for the system operator.

Orientation on international best practices

It is totally appropriate to copy large parts from existing documents. This has been done by Chile and MISO. It is definitely beneficial to orientate on international best practices, since the more different countries are aligned, the easier it is to adapt from one country to another for manufacturers. It will facilitate a competitive market and interoperability. However, if guidelines or parts of them are copied, this should only be done carefully and the guidelines must be adapted to the specific needs of the Kazakh power system.

Verification

The verification of GFM capabilities can be done via measurements or simulations. It is important that each of the requirements is tested. Tests in grid connected mode and island mode should be conducted. The tests should be described clearly including the test setup, initial operation points and the applied events.

In addition, it is crucial to define clear success criteria for each test, which consider the GFM requirements.

8 References

[1] "Grid forming capability of power park modules - Report on technical requirements", ENTSO-E, 03. October 2025

[2] "Voluntary Specification for Grid-forming Inverters", AEMO, May 2023

[3] "Voluntary Specification for Grid-forming Inverters: Core Requirements Test Framework", AEMO, January 2024

[4] "Requisitos Técnicos Mínimos para Recursos Basados en Inversores Grid-Forming", CEN, October 2024

[5] "Technical requirements for grid-forming capabilities including provision of inertia", VDE FNN, May 2025

[6] "European Connection Conditions", National Grid, 11. June 2025

[7] "European Compliance Process", National Grid, 19. May 2025

[8] "Krav Til Transmissionstilsluttede Energilageranlæg Med Grid Forming Kapabilitet", Energinet, 14. November 2025

[9] "MISO Grid-Forming Battery Energy Storage Capabilities, Performance, and Simulation Test Requirements Proposal", MISO, July 2024

[10] "White Paper: Grid Forming Functional Specifications for BPS-Connected Battery Energy Storage Systems", NERC, September 2023

[11] "Grid Code Specifications for Grid Energy Storage Systems SJV2024", Fingrid, 15. January 2025

[12] "UNIFI Specifications for Grid-Forming Inverter-Based Resources Version 2", UNIFI Consortium, 21. March 2024

[13] "Advanced Grid Support Energy Storage Resource (AGS-ESR) - Functional Specification and Test Framework for the ERCOT Grid", ERCOT, September 2024

[14] "Amended RfG Regulation" (RfG 2.0), ACER, December 2023