

Managing converter stability through grid forming

9.10.2026



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1 Introduction

The purpose of this document is to provide the technical background for the measures needed to manage converter stability in the Finnish power system. The document serves as background information for new requirements for power park modules. The document describes the stability challenges observed in the Finnish power system and presents grid-forming capability as a means of mitigating them.

Chapter 2 presents a background for the paper including challenges in converter dominated power system, experiences related to converter-driven oscillations and fault ride through in the Finnish power system. Chapter 3 presents the motivation for grid forming including key features of grid forming, development of ESCR in the Finnish power system and studies showing the effectiveness of grid forming as a mitigation measure. Chapter 4 discusses the new technical requirements set for wind and solar power plants. Chapter 4 includes proposed ESCR based dimensioning principles along with discussion on comparison of centralised and distributed compensation strategies. Chapter 5 summarises the main conclusions and the proposed allocation of responsibilities between transmission-level and connection-specific measures.

2 Background

2.1 Transition to converted dominated grid

The large-scale integration of renewable production has introduced new stability phenomena and study needs compared with those of a traditional synchronous-generator-dominated power system. Many of these aspects are becoming increasingly relevant as the share of inverter-based resources (IBRs) increases because of the connection of renewable generation and the decommissioning of synchronous generators [1].

Traditionally, electricity has been produced with hydro and turbo generators. In synchronous generators, the turbine rotates the rotor synchronised to the grid frequency. Synchronous generators have an inherent capability to resist frequency and voltage changes occurring in the network. Wind and solar power plants are typically connected to the grid via power converters. The IBRs do not have such inherent capabilities as synchronous generators to resist frequency and voltage changes nor to inject fault current. The control system of an IBR measures electrical quantities, such as voltage magnitude and angle, and responds to system changes according to its control design. Grid-following inverters (GFL) are currently the most widely used technology for integrating IBRs into the power system. They mainly rely on phase-locked loop (PLL) control to synchronise with the grid.

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GFL technology requires synchronous generators or other grid forming (GFM) devices to operate in a stable manner. In GFL inverters, PLL is typically used to track the phase angle and frequency of the grid voltage. Using this information, the inverter can be controlled to inject current with the desired magnitude and phase angle into the grid. GFL inverters are known to be prone to instability if the share of IBRs is high compared with synchronous generators or other GFM type devices in the area. [2]

Finland has already experienced converter-driven oscillations and fault ride-through challenges in areas with high penetration of wind power. These challenges have resulted in operational measures, new technical requirements for connecting customers and investments in grid-strengthening assets. While transmission-level synchronous condensers (SynCons) and GFM devices can improve system strength, an alternative approach is to require additional GFM capability from new wind and solar projects. This paper compares centralised and distributed compensation strategies through electromagnetic transient (EMT) simulations and proposes an ESCR-based dimensioning principle for allocating the required GFM capability in low-ESCR areas.

2.2 Converter-driven oscillations

Converter-driven stability phenomena are commonly classified as fast or slow, depending on the dominant control interactions and associated timescales. The slow converter-driven instability is mainly driven by the slower control loops of the IBR such as PLL, voltage controller, reactive or active power controller. Fast converter-driven instability is mainly driven by faster control loops such as current control loops. Typically, oscillations associated with the control interactions of wind and solar power converters occur due to slower-level control loops and are categorized as slow converter-driven oscillations. [2]

Slow converter-driven oscillations have been a significant challenge on the west coast of Finland since 2021 due to the high share of wind power in the region. Fingrid has seen converter-driven voltage oscillations both in simulation models and in real-life events. As discussed in [1], the slow converter-driven stability issue in the Finnish power system cannot be eliminated solely by revising the tuning of plant-level voltage controllers. Fingrid has also been able to validate the capability of the simulation models to correctly represent the oscillations through the arranged real-life grid test. [1,5]

Due to poor damping of these converter-driven oscillations in high wind scenarios, there has been a need to curtail wind generation during transmission line outages. Fingrid has invested in Jylkkä SynCon (commissioned in 2025) and Kristinestad GFM STATCOM (expected to be commissioned in 2027) to improve the damping of converter-driven oscillations. At present, possibility to install two new SynCons in 2030-2031 is being investigated.

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Through grid code specifications for power generating facilities (VJV2024 [6]), there has also been increased focus on improving the capabilities of wind and solar power plants to reduce their negative impact on the damping of converter-driven oscillations. In addition to the traditional short-circuit ratio, customers are provided with an equivalent short-circuit ratio (ESCR) that accounts for the influence of other inverter-based resources, such as nearby wind and solar power plants [3]. Customers have also been provided with an EMT model called the ESCR testbench [4] which they shall use to demonstrate the capability of GFL inverters to operate in a low-ESCR environment.

Requirement for fast initial response of voltage control (VJV2024, Section 18.2.2) and the ESCR testbench requirement have been found to significantly improve the response of wind and solar plants to converter-driven oscillations. However, recent studies carried out in 2025-2026 have shown that even advanced GFL inverters reduce the damping of converter-driven oscillations as the amount of GFL inverters relative to synchronous generation reaches a certain level. This negative effect can be compensated by increasing the system strength (i.e. by introducing a new SynCon or GFM converter) as shown in Chapter 3 of this paper.

2.3 Fault ride through capability of wind and solar

Fault ride through (FRT) capability of the wind or solar plant is verified as a part of the grid connection process through electromagnetic transient (EMT) and phasor-domain (PDT) simulations. However, these simulations contain only simplified representations of the network and lack detailed models of other IBRs in the vicinity. There is generally very little research on the simultaneous fault ride through behaviour of multiple power plants in a situation where a fault occurs within an area of high penetration of IBRs. Although these FRT-related challenges do not fall strictly within the converter-driven stability category and do not fit well into any established stability category, they are nevertheless closely related to the stable operation of converter-based generation and thus included under the topic of “converter stability” in the context of this paper.

GFL wind and solar power plants are dependent on the synchronisation of the PLL to remain connected to the grid. This synchronisation can be compromised by sudden changes in the grid, such as faults, and loss of synchronism can lead to the disconnection of the plant. PLL loss of synchronism can occur when the PLL synchronises to a local voltage vector that is mostly generated by the IBR itself. This can happen when a fault in the grid and the resulting voltage dip causes the IBR to enter low voltage ride through (LVRT), during which it operates in current control mode injecting active and reactive current as defined by grid codes [5]. If the grid strength is sufficiently weak, the active current injection might cause the local frequency to temporarily increase or decrease, which will create an angle difference between the grid voltage vector and the local voltage vector. Since the IBR’s PLL tracks the local voltage vector, there will be a rapidly increasing angle difference between the grid and

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the PLL as well. Transients in active and reactive power output, resulting from PLL loss of synchronism, can ultimately lead to plant disconnection from the grid, for example due to overvoltage in AC or DC side or poor voltage quality causing the anti-islanding protection to operate.

Simulation studies conducted by Fingrid have shown that existing wind power plants in western Finland have severe issues to track the voltage angle during the fault and might lead to disconnection of some of the wind power plants. Most of these wind power plants are built according to older grid code VJV2018. Newer power plants built according to VJV2024 are seen to perform in a more robust manner in existing grid due to their weak grid converter controls. However, simulation studies have shown that, in weak grid conditions, GFL wind and solar power plants built according to VJV2024 requirements may not be sufficient to prevent loss of synchronism and subsequent tripping of wind and solar plants. As the share of inverter-based generation increases, maintaining adequate system strength becomes increasingly important, and additional measures such as synchronous condensers or GFM converters may be required.

3 Motivation for grid forming

3.1 Grid forming resources in the Finnish Power System

Stable operation of GFL inverters becomes increasingly challenging as the share of IBRs increases and the available system strength decreases. Additional GFM capability can provide the voltage reference and system strength required under these conditions. GFM IBRs are needed to compensate for the reduction of synchronous generation and external system strength required by present GFL inverters to function properly. In Finland, the need has become obvious in some regions, for example in the coastal region of Ostrobothnia, where the majority of wind power plants are located. In these regions, further GFL connections are not possible without grid strengthening measures as it would endanger the stable operation of the power system.

By common definition, a GFM resource shall be able to self-synchronise, operate in stand-alone mode and provide synchronisation services which include synchronising power, system strength, fault current and virtual inertial response. GFM capabilities are required from all BESS systems of 10 MW and above in Finland by the grid code SJV2024 [7]. Several grid-forming battery energy storage system (GFM BESS) projects have been successfully integrated into the Finnish power system to provide instantaneous frequency and voltage support that cannot be provided by GFL IBRs. However, the majority of these GFM BESS systems have not been located in IBR dominated areas of Finnish power system.

Key features of GFM to ensure the capability of Finnish power system in IBR dominated areas include:

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1) Capability to improve system strength autonomously

- Inherent capability to resist grid voltage angle changes by injecting or absorbing active power in subtransient to transient timeframe.
- Inherent capability to resist grid voltage magnitude changes by injecting or absorbing reactive power in subtransient to transient timeframe.

2) Capability for non-amplifying response in voltage and frequency oscillations that might occur in the power system. This includes electromechanical modes, converter-driven oscillations and subsynchronous resonances that might occur over a wide frequency range.

3) Capability to balance the system voltage by injecting positive and negative sequence currents.

The ultimate long-term target is to offer these capabilities through wind and solar power plants themselves. While the technology is still in the development phase, these capabilities can be provided by separate GFM systems such as a synchronous machine, GFM BESS or GFM static synchronous compensator equipped with energy storage (ES-STATCOM).

3.2 Development of ESCR in the Finnish Power System

Traditionally, the short-circuit ratio (SCR) has been used to assess the strength of the grid at a generator's point of connection. However, SCR only considers the short-circuit strength of the network and the rating of the generator. In a grid with a high penetration of IBRs, multiple IBRs share the available grid strength and interact with each other through the network. As a result, SCR may overestimate the actual strength experienced by an IBR. One way to evaluate "shared" SCR between IBRs is ESCR. ESCR is defined in the CIGRÉ publication [8]. Fingrid has also published a White Paper document, [9], which provides additional information on the topic.

In Fingrid's ESCR calculation, all the IBRs in the system are considered. In systems without GFM plants, the network short-circuit contribution is determined solely by synchronous generators. The interaction factors are derived from power-flow simulations. First, the voltages at all IBR plants are recorded. A shunt capacitor is then added at the connection point of the studied plant, a new power-flow calculation is performed, and the resulting voltage changes are measured. During this process, transformer tap changers and controllable shunt devices are fixed, while synchronous generators remain free to regulate voltage.

GFM plants are treated differently because they contribute to system strength rather than weaken it. Consequently, they are excluded from the denominator of the ESCR calculation. In Fingrid's methodology, each GFM plant contributes to the network

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strength by an amount equal to three times its maximum active power. In addition, GFM plants participate in voltage control in a manner similar to synchronous generators. This reduces the interaction factors between plants and significantly increases the resulting ESCR values.

The development of ESCR values in year 2028 and 2031 is shown in Figure 1 and Figure 2, respectively. The scenario of Figure 1(a) for year 2028 includes only the IBRs without any GFM BESS. Addition of GFM BESS units expected to be connected by 2028 in a certain growth scenario would lead to situation of Figure 1(b). The scenario for year 2028 and 2031 includes roughly 13 GW and 20 GW of wind and solar IBRs with GFL technology, respectively. The ESCR simulations included two different scenarios for GFM BESS units: Scenario A includes a total of 2.2 GW and scenario B has 4.4 GW of GFM BESS units. Large amount of the GFM BESS units both scenarios is located in the converter dominated areas.

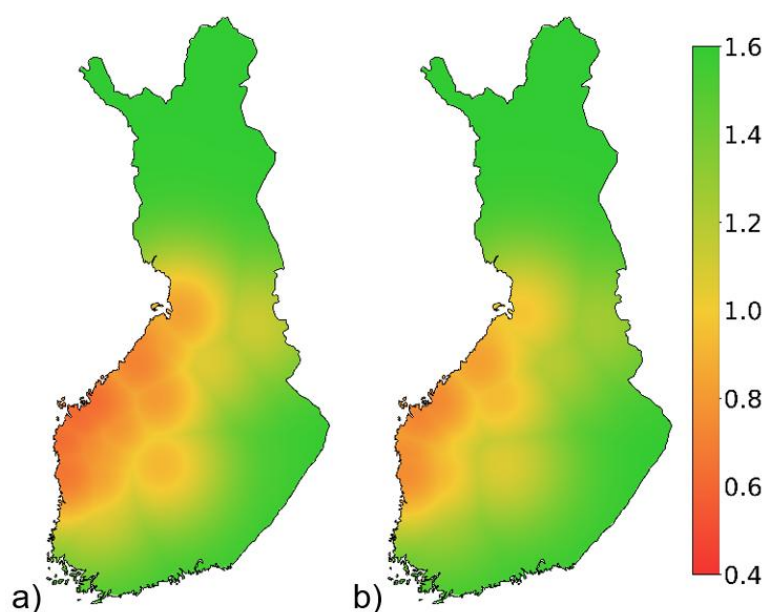


FIGURE 1. SIMULATED ESCR VALUE IN YEAR 2028 A) WITHOUT GFM BATTERIES, B) WITH A CERTAIN AMOUNT OF GFM BATTERIES.

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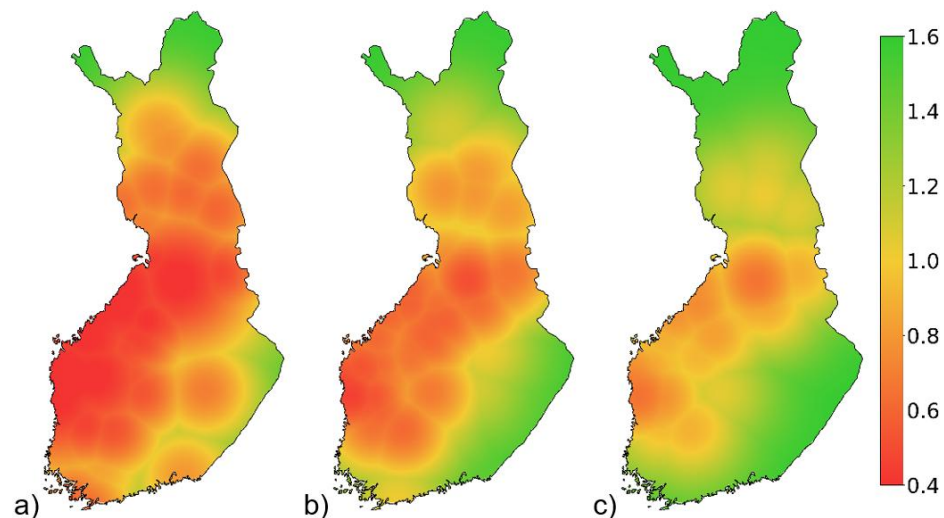


FIGURE 2. SIMULATED ESCR VALUE IN YEAR 2031 A) WITHOUT GFM BATTERIES, B) GFM BATTERIES IN SCENARIO A, C) WITH GFM BATTERIES IN SCENARIO B.

3.3 Studies on mitigating converter-driven oscillations with GFM converters

Simulations representing a future scenario with roughly 2 GW of new wind or solar power plant connections showed that high amplitude converter-driven voltage oscillations might occur in case mitigation measures are not applied. Possible options included synchronous condensers, GFM BESSs, GFM STATCOMs without dedicated energy storage, and ES-STATCOMs with dedicated energy storage. Studies have shown that each of these solutions, including GFM STATCOM without dedicated energy storage, can improve the damping of voltage magnitude oscillations.

Figure 3 shows the example of the simulation results with several different GFM BESS original equipment manufacturers (OEMs) in different operating points. To quantify the effectiveness of the GFM battery systems, a hosting ratio was defined as the maximum additional wind or solar capacity that could be connected before the damping of the studied converter-driven oscillation became unacceptable. In the studied network, the response was considered acceptable if the sustained post-disturbance voltage-magnitude oscillation remained within $\pm 2\%$ of the pre-disturbance voltage magnitude at all monitored transmission-system buses. The hosting ratios presented in Figure 3 were obtained by gradually increasing the amount of additional wind or solar generation in the EMT simulations.

Simulations show that GFM BESS devices can host approximately 1...4 times wind or solar depending on the OEM and operation point of the BESS. The results vary significantly between OEMs due to differences in control implementation and tuning. All GFM BESS systems, however, provided a positive damping effect.

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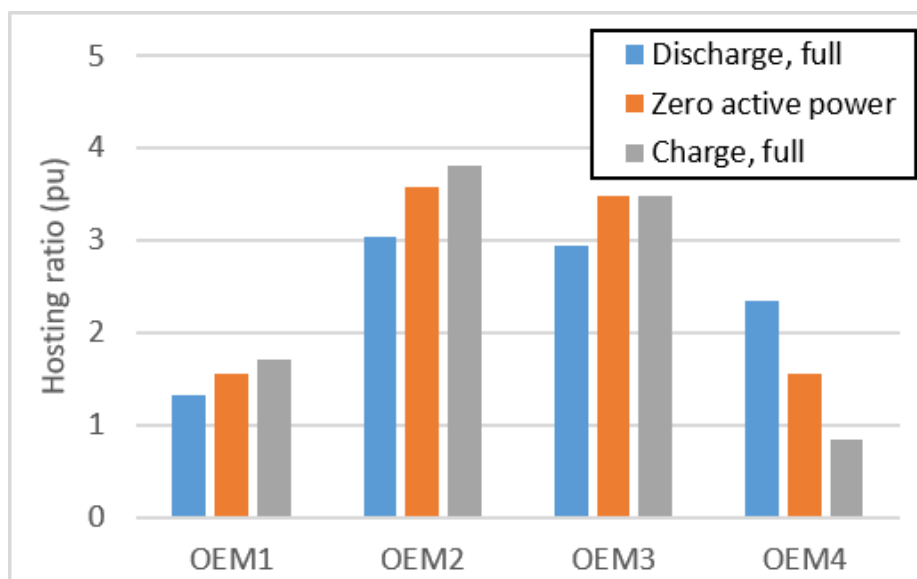


FIGURE 3. HOSTING RATIO OF GFM BESS IN DIFFERENT OPERATING POINTS FOR CONVERTER-DRIVEN OSCILLATIONS.

3.4 Studies on mitigating fault ride through challenges with GFM converters

Fault ride through simulations have been performed on a wide-area EMT model, which represents a future scenario with prediction on new wind or solar power connections. The model consisted of roughly 200 wind power plants, around 3000 buses, multiple series capacitors, one 300 MVA static synchronous compensator (STATCOM) and one 200 MVA SynCon unit ($S_k'' = 1000$ MVA). The ratings of these devices were based on existing investments. [10]

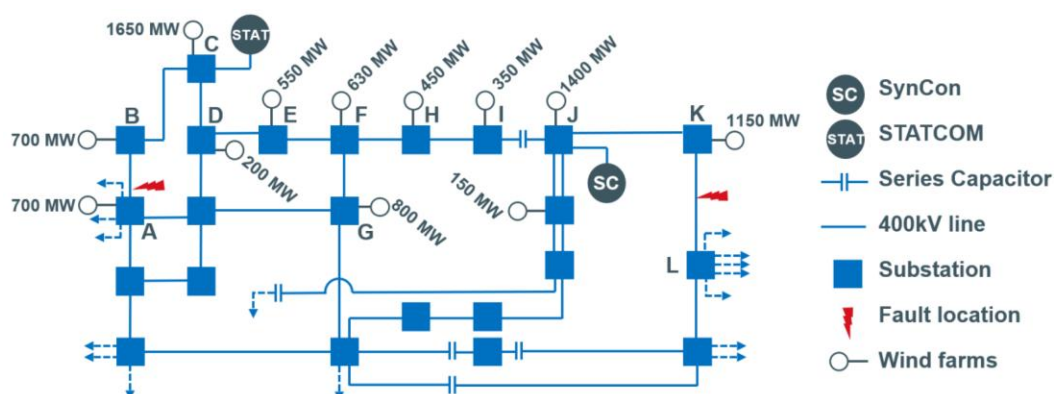


FIGURE 4. REPRESENTATION OF THE STUDIED SECTION OF THE WIDE-AREA MODELLED 400 kV NETWORK [10].

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SynCons and GFM batteries were added to the model as supplementary compensation devices. Figure 4 represents the studied area of the 400 kV network of the wide-area EMT model. Three-phase-to-ground faults were simulated on the lines between substations A and B and K and L. Additional SynCons were modelled using the same 200 MVA model ($S_k'' = 1000$ MVA), which is used for the SynCon at substation J. [10]

The simulations showed that approximately 1.7 GW of generation could be lost because of loss of synchronism if no mitigation measures were applied. This outcome was considered unacceptable from an operational-security perspective because the simulated generation loss of approximately 1.7 GW exceeded the applicable 1.3 GW reference incident. [10]

A centralised network-level solution based on new synchronous condensers was found to be effective in reducing the amount of wind generation disconnected following the fault. Figure 5 presents the voltage phase-angle response measured at the wind power plant connected to bus B during the fault and after fault clearing. For this reason, the SynCon located at bus B limits the angle drift shown in the figure more effectively than the SynCon located at bus I. This does not imply that the SynCon at bus I is unnecessary. The voltage-angle deviation also increases in the area around bus I, where wind power plants may disconnect without local compensation.

The results therefore show that synchronous condensers are needed in both areas and that their stabilising effect is primarily local. The effectiveness of centralised compensation consequently depends on the electrical location of the devices relative to the wind and solar power plants requiring support. If the future location and timing of new projects differ from the planning assumptions, centralised compensation may not provide adequate stabilising support in all affected areas.

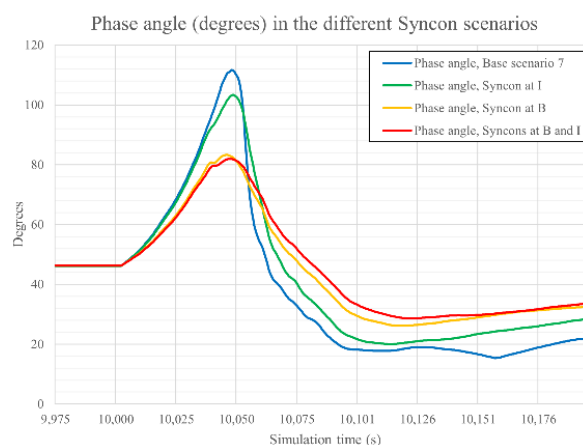


FIGURE 5. PHASE ANGLE OF WIND POWER PLANT CONNECTED TO SUBSTATION B IN SCENARIOS WITH SYNCONS AS A CENTRALISED SOLUTION [10].

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An ES-STATCOM was also found to be effective in limiting voltage-angle deviation during and after the fault and in preventing wind and solar power plants from tripping. GFM STATCOM without dedicated energy storage was not found to be viable due to limited energy available in MMC (Modular Multilevel Converter) submodule capacitors that limit inherent GFM active power response during the fault and fault clearing. This result does not contradict the oscillation-damping results presented in Section 3.3 . Damping of the studied voltage-magnitude oscillation was primarily supported by the fast voltage and reactive-power response. In contrast, limiting the voltage-angle deviation during and after a fault required a sustained active-power response that could not be provided solely from the energy stored in the MMC submodule capacitors.

Distributed solution with GFM BESS systems were similarly seen as an effective solution for loss of synchronism. Simulations with additional GFM BESS systems, presented in Figure 6 shows phase angle movements with 90...450 MW of GFM BESS distributed in 9 different locations. [10]

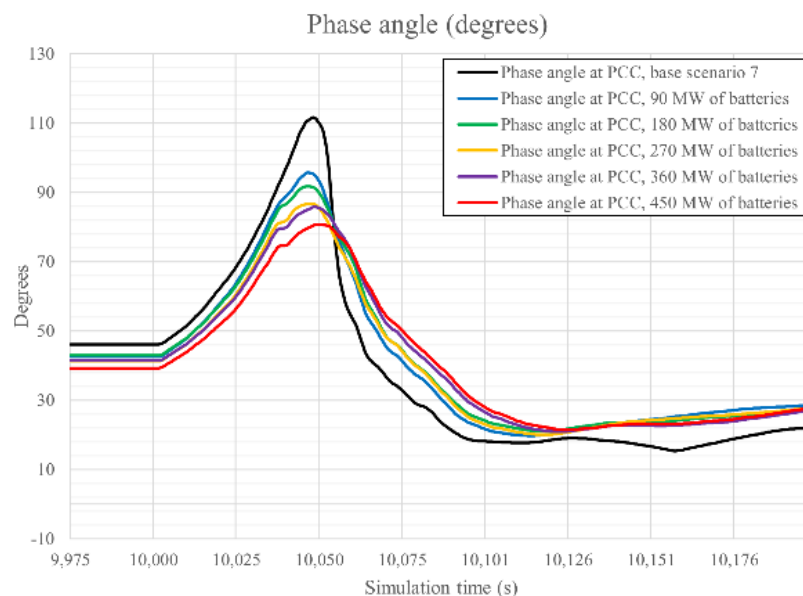


FIGURE 6. PHASE ANGLE OF WIND POWER PLANT CONNECTED TO SUBSTATION B IN SCENARIOS WITH ADDITIONAL BATTERIES AS A DISTRIBUTED SOLUTION [10].

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4 New technical requirements for wind and solar power plants

4.1 Proposed ESCR-based dimensioning principle for GFM capability

Additional GFM capability is proposed for wind and solar power plants for which the ESCR value provided by Fingrid is below 1.0. An ESCR value of 1.0 or above removes the additional GFM requirement but does not replace the general stability and compliance requirements applicable to the power plant. The value is determined by Fingrid's network-planning process, taking into account existing and agreed future connections. The capability may be provided either through the plant's inherent controls or by a supplementary compensation device. The compensation device can be either GFM BESS, GFM ES-STATCOM or a synchronous machine such as SynCon.

The proposed dimensioning is intended to compensate for the destabilising effect caused by the connection of a GFL power plant. The dimensioning is shown in Table 1. The required compensation level should be proportional to the stabilising effect that can be provided by the additional GFM resource. Therefore, the dimensioning is derived from the hosting-capacity relationships observed in the dynamic simulations. As shown in Section 3.3 a well-tuned GFM BESS has the capability to host GFL IBRs equivalent to approximately 3–3.5 times its nominal capacity. The inverse of this hosting ratio corresponds to a required GFM BESS rating of approximately 29–33% of the connected GFL plant rating. The proposed 30% requirement for ESCR below 0.7 therefore represents the screening level at which the supplementary device is expected to compensate for the destabilising contribution of the connected GFL plant.

TABLE 1. DIMENSIONING ON ADDITIONAL COMPENSATION DEVICE

ESCR	GFM BESS ($P_{\text{BESS}}/P_{\text{max}}$)	GFM ES-STATCOM ($P_{\text{ESTAT}}/P_{\text{max}}$)	Synchronous machine (S_k''/P_{max})
ESCR ≥ 1.0	-	-	-
$0.9 \leq \text{ESCR} < 1.0$	$\pm 10 \%$	$\pm 7 \%$	33 %
$0.7 \leq \text{ESCR} < 0.9$	$\pm 20 \%$	$\pm 13 \%$	66 %
ESCR < 0.7	$\pm 30 \%$	$\pm 20 \%$	100 %

For an ES-STATCOM, a representative hosting ratio of approximately five is assumed because its energy-storage capacity and converter operating range can be reserved for grid support rather than being constrained by energy-market operation. The inverse of this ratio gives a required active-power rating of approximately 20% of the GFL plant rating. For a synchronous condenser, the corresponding threshold is expressed using

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subtransient short-circuit power. A ratio $\frac{S_{k''}}{P_{max}} = 1.0$ is used in the lowest-ESCR class, which is analogous to providing a local short-circuit contribution equal to the connected plant rating.

The intermediate requirements are deliberately graded rather than derived as independent sharp stability boundaries. As the pre-connection ESCR approaches 1.0, the existing network provides a larger share of the system strength required for stable operation; the supplementary device is therefore dimensioned at approximately one-third or two-thirds of the maximum low-ESCR requirement. This results in BESS requirements of 10%, 20%, and 30%; ES-STATCOM requirements of 7%, 13%, and 20%; and synchronous-condenser requirements of 33%, 66%, and 100% for the three ESCR bands. The stepwise values provide a practical dimensioning guideline for new connections that will be implemented with a variety of equipment from different OEMs while recognising that the actual stability boundary is continuous and technology dependent.

The ratios are referenced to the rated active power, P_{max} , of the new GFL plant. For converter-based devices, the stated percentage means the minimum active-power capability available in both directions. The required GFM capability is defined through demonstrated dynamic performance rather than reserved market headroom. Compliance shall be verified for the relevant operating points through EMT simulations.

Because the stabilising effect is strongly dependent on electrical location, a supplementary device is required to be located electrically close to the associated GFL plant and to remain connected to the same network section under the relevant contingencies.

Because the stabilising effect is strongly dependent on electrical location, a supplementary device is required to be located electrically close to the associated GFL plant and to remain connected to the same network section under the relevant contingencies. The 60 km limit was selected based on EMT studies of converter-driven oscillations, which showed that the damping contribution of a GFM BESS remains of a similar order of magnitude at distances up to approximately 60 km. Beyond this range, the stabilising effect becomes increasingly dependent on wider network topology and the presence of alternative electrical paths, making the allocation of stabilising support to a specific GFL plant less clear. From a fault ride-through perspective, the GFM BESS should also remain electrically connected to the associated GFL plant during and after relevant faults so that the stabilising support remains available throughout the disturbance and recovery.

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4.2 Comparison of centralised and distributed compensation strategies

Both centralised and distributed compensation can provide the GFM capability required to maintain converter stability, but their practical characteristics differ. Centralised synchronous condensers and ES-STATCOMs can support several existing and future connections and can be specified, validated, and operated directly by the TSO. They are particularly appropriate when the need arises from an existing fleet, committed connections, system-wide security margins, or interactions that cannot be allocated reliably to a single project. Comparison of centralised and distributed compensation strategies is presented in Table 2.

The principal limitation of centralised compensation is its sensitivity to location, timing, and generation-development uncertainty. Large transmission-level assets must be planned several years in advance. If the realized projects differ from the forecast, the asset may be commissioned too late, may be oversized, or may be electrically too distant from the plants requiring support. The FRT results in Section 3.4 demonstrate that equal synchronous-condenser ratings at different buses can produce substantially different angle-stabilising effects. A centralised compensation system also involves a significant availability risk, as unexpected outage of the equipment may lead to power curtailment needs across a large number of GFL power plants.

Distributed compensation is commissioned with the plant that creates the incremental need and is located electrically close to that plant. It therefore scales with actual IBR development and reduces the risk of a suboptimally located transmission investment. Customer-provided capability follows actual project development instead of requiring the TSO to predict future project locations several years in advance. A GFM BESS may also participate in energy and reserve markets, and a hybrid plant may make more effective use of the connection capacity.

TABLE 2. COMPARISON OF CENTRALISED AND DISTRIBUTED COMPENSATION STRATEGIES TO MANAGE CONVERTER STABILITY

Centralised compensation	Distributed compensation
Requires advance forecasting and planning	Scales with actual IBR development
Effectiveness depends strongly on location	Located electrically close to the plant
Can provide support for several connections	Matches to the need of the connecting plant
Risk of being oversized or poorly located	Dimensioned according to local ESCR
A single outage may affect several plants	Limits outage risks to individual connection

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The studies presented in Sections 3.3 and 3.4 establish a direct relationship between additional GFL generation, declining local system strength and deteriorating dynamic performance. As ESCR decreases, connecting more GFL wind and solar power plants reduces oscillation damping and increases the risk of PLL loss of synchronism during and after faults. These effects cannot be eliminated solely through improved GFL controls; beyond a certain IBR penetration, additional GFM capability is required. The relevant question is therefore how this capability should be provided and who should be responsible for it.

Stable operation is an indispensable condition for connection to the power system, and the plant owner must demonstrate during design and compliance verification that the complete facility remains stable under the specified network conditions. Where a new GFL plant would reduce the stability margin below an acceptable level, requiring appropriately dimensioned stabilising equipment is analogous to requiring e.g. fault ride-through capability or other properties that ensure reliable and safe operation of the facility as part of the power system. When dimensioned according to principle presented in Section 4.1 the stabilising equipment restores the compatibility of the connecting facility and cannot be interpreted as a system-wide ancillary service supplied to the TSO or other network users as it will only cancel out the stability deteriorating effect of this specific plant being connected to the grid.

An ESCR-based requirement translates this principle into a proportionate connection rule. ESCR reflects both the strength of the surrounding network and the cumulative influence of nearby IBRs. No additional equipment would be required at sufficiently strong connection points, whereas the obligation would increase as ESCR decreases. Existing credible GFM resources should improve the assessed conditions and reduce the requirements. The approach therefore allocates mitigation according to the connection's actual stability impact instead of imposing a uniform requirement on projects with materially different effects.

This allocation does not eliminate the need for all centralised investments. There may still be a need for transmission-level devices to ensure reliable operation of existing generation, to cover modelling uncertainty or to increase system-wide security margins. The efficient strategy is layered: centralised assets provide a baseline for the existing system, while each new plant prevents its connection from eroding that baseline. With transparent ESCR inputs, advanced disclosure and verification using validated EMT models, an obligation on new wind and solar projects in low-ESCR areas is technically targeted, timely and economically preferable to an open-ended programme of centralised compensation. It also creates a durable incentive to integrate GFM capability into future plants.

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4.3 Updated functional requirements and compliance verification for GFM converters

The proposed dimensioning principle will be supported by updated functional requirements and simulation tests for GFM converters. The detailed requirements and compliance procedures are specified separately [11] and are therefore not repeated in this paper.

The existing Fingrid requirements for GFM BESS installations [7] focus primarily on ensuring the stable operation of the GFM unit itself. Where a GFM BESS or an ES-STATCOM is used as a supplementary device for a GFL wind or solar power plant, the requirements will also address its ability to support the stable operation of the combined facility. This includes demonstrating sufficient stabilising performance across the relevant operating range of both the GFM device and the associated GFL plant. For supplementary GFM devices, the verification also demonstrates the capability to stabilise the associated GFL plant, including the damping of voltage-magnitude and voltage-angle oscillations and the prevention of fault-induced loss of synchronism.

The required performance cannot be determined solely from the rated power of the GFM device or from the selected control concept. As shown in Section 3.3 the hosting capability may vary between implementations and operating points. The dimensioning principle presented in Section 4.1 therefore provides an initial minimum rating, while final compliance is demonstrated through performance-based EMT simulations covering the relevant operating points and network conditions.

Separate functional requirements and simulation tests will be introduced for wind and solar power plants that provide GFM capability through their own converters. For these plants, the objective is to demonstrate sustained voltage-source behaviour within the available current, power and energy limits, stable operation during and after disturbances, and the absence of adverse interactions under weak-grid conditions. Unlike a supplementary GFM device, an inherently GFM wind or solar power plant is not expected to provide additional hosting capability for a separate GFL plant unless this is explicitly included in the applicable connection requirements.

The functional requirements, simulation tests, and acceptance criteria may be refined as additional validated models and operational experience from utility-scale GFM wind, solar, BESS, and ES-STATCOM installations become available. Any such refinements will maintain the performance-based objective of ensuring stable operation of both the connected facility and the surrounding power system.

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5 Conclusions

The increasing concentration of grid-following inverter-based resources is reducing system strength in several parts of the Finnish power system. Wide-area EMT studies indicate that improved grid-following controls can increase robustness but cannot, in all cases, prevent poorly damped converter-driven oscillations or fault-induced loss of synchronism.

Synchronous condensers, GFM BESSs, and ES-STATCOMs were found to provide effective stabilising support. Their effectiveness depends on their electrical location, control implementation, operating point, and available active and reactive power capability. A GFM STATCOM without dedicated energy storage was able to improve the damping of the studied voltage-magnitude oscillations but did not provide sufficient sustained active-power response to mitigate the loss of synchronism problem.

Based on these results, additional GFM capability is proposed for new wind and solar power plants for which the ESCR value provided by Fingrid is below 1.0. The capability may be provided through GFM controls integrated into the plant converters or by a supplementary GFM BESS, ES-STATCOM, or synchronous machine. The proposed ESCR-based ratings provide an initial minimum dimensioning rule, while final compliance is demonstrated through the performance-based EMT simulations specified in the applicable connection requirements.

The proposed approach does not remove the need for transmission-level investments. Centralised assets remain necessary to support existing generation, maintain system-wide security margins, and manage uncertainties that cannot be assigned to individual connections. A layered approach is therefore recommended: Centralised assets establish the required baseline system strength, while new connections prevent their own integration from eroding that baseline.

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