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Specific study requirements for power park modules connected to converter-dominated areas

Change log

Date	Version	Changes
9.10.2026	1.0	First official release.
2.11.2026	1.01	Editorial and linguistic clarifications and minor corrections. No changes to the technical content of the requirements.

1 Introduction

This document sets out specific study requirements for type D power park modules (converter-connected power plants) that are connected to converter-dominated areas of the Finnish power system. The requirements are set based on the specific study requirements in the Grid Code Specifications for power-generating facilities (see VJV2024 Chapter 5).

Together with equipment manufacturers, Fingrid has investigated the capability of power park modules to operate in the converter-dominated areas of the power system in 2022–2026. In this document, the converter dominance at the point of connection is assessed based on the equivalent short-circuit ratio (ESCR). The ESCR value describes the converter dominance of the grid from the point of connection of the power plant, i.e. the voltage and angle stiffness produced by synchronous machines and other grid-forming equipment (GFM) in relation to the active power of grid-following (GFL) power plants, considering the electrical distances between them.

Based on Fingrid's studies and analyses presented in a study in the field, GFL power park modules may cause unattenuated or weakly attenuated converter-driven oscillation in converter-dominated areas. In addition, the fault ride-through capability of power park modules has been found to be poor in converter-dominated areas. Power park modules have been found to cause significant overvoltage to the grid and to the DC link of the power plants' converters during three-phase short-circuits in converter-dominated areas of the grid. Overvoltage is caused by the unstable behaviour of the power plants' control system and, in certain situations, pose a risk of large-scale disconnections of power plants.

The optimisation of the control parameters, implemented in cooperation with the equipment manufacturers, has been able to significantly reduce the risk of converter-driven voltage oscillation and improve the operation of power plants in the grid faults. However, ensuring sufficient voltage and angle stiffness of the voltage is particularly challenging in converter-dominated areas where the proportion of GFM equipment is low.

In practice, sufficient performance cannot be achieved alone by optimising the control parameters.

Based on the technical analyses carried out by Fingrid, correctly implemented GFM control has the inherent capability to prevent the issues described above. The GFM equipment aims to counteract changes in the voltage phasor by responding to phase angle changes of the grid voltage with an almost immediate active power response and to changes in the amplitude of the grid voltage with an almost immediate reactive power response. The analyses have found that the reactive power response, which improves the amplitude stiffness of the voltage, is essential for attenuating converter-driven voltage oscillation. The active power response, which resists voltage phase angle changes, has been found to be essential for ensuring the fault ride-through capability of a power park module in converter-dominated areas.

These features are necessary to ensure the stable operation of the power park module, which is an absolute prerequisite for the fulfilment of Fingrid's Grid Code Specifications for power-generating facilities (see VJV2024, Chapter 18.2.1) and thus for the connection of the power park module to the grid. The characteristics described above can be implemented, as outlined in Chapter 2 , either by means of GFM control integrated into a power park module or by connecting a dedicated GFM device in the vicinity of the power plant's point of connection. Such dedicated supplementary devices may be a battery energy storage system (BESS), an energy-storage-equipped static synchronous compensator (ES-STATCOM), or a synchronous machine, such as a synchronous condenser.

Fingrid has published a technical report on the subject on its website [1].

2 Scope of requirements and demonstration of compliance

The specific study requirements presented in this document apply to all type D power park modules connected to the Finnish power system with an ESCR value of less than 1.0 at the point of connection.

Fingrid determines the ESCR values as part of its continuous planning process, and the magnitude of ESCR values are determined on the basis of existing and agreed connections that have not yet been built. Very low values, below ESCR < 1.0, occur in areas dominated by wind power where the number of synchronous machines is small or which are far from synchronous machines.

Fingrid will provide the ESCR value to the facility owner as part of the assessment of the specific study requirements in accordance with Chapter 5 of the VJV2024. The assessment is carried out at the request of the facility owner at the beginning of the verification process of the requirements, in stage 0 (VJV2024, Chapter 6.4.3.2) before the connection agreement is signed. The facility owner must request an assessment of the specific study requirements from Fingrid, regardless of whether the power plant is going to be connected to Fingrid's network or to the network of another network operator, such as a distribution system operator.

The studies required in this document are carried out as part of the compliance monitoring process in accordance with VJV2024, in stage 1. However, Fingrid

recommends that the facility owner verify the compliance of the requirements with the preliminary design values of the power plant already in stage 0 (before the equipment is purchased).

The equipment manufacturer may request the model testing tools described in this document to assess the compliance of the technology. Fingrid always assesses the compliance of a power plant on a plant-by-plant basis and does not issue certificates for individual devices or maintain a list of equipment that meet the requirements. However, the equipment manufacturer may receive a statement from Fingrid on the capability of its technology to meet the requirements presented in this document on a general level.

3 Requirements

3.1 Grid-forming control requirements

A power park module is required to have the capability to GFM control, either by the power plant's own control or by supplementary device, if the ESCR value delivered by Fingrid to the power plant is below the value of 1.0. The minimum dimensioning of the supplementary device is determined based on the ESCR value delivered to the power park module. The dimensioning of the different supplementary device is presented in Table 1. The facility owner selects the type of supplementary device.

In the case of battery energy storage system (BESS), the rated value is based on the rated capacity of the BESS ($P_{BESS,}$ the same value for the production and consumption mode) in relation to the rated capacity (P_{max}) of the power park module to be connected. Correspondingly, in the case of ES-STATCOM, the rated value is based on the rated capacity of the ES-STATCOM energy storage facility (P_{ESTAT}) in relation to the rated capacity of the power park module to be connected. With a synchronous machine, the rated value is based on the subtransient short-circuit power (S''_k) of the synchronous machine in relation to the rated capacity of the power park module to be connected.

Table 1. Requirement for the rated capacity of the supplementary device.

ESCR	BESS (P_{BESS} / P_{max})	ES-STATCOM (P_{ESTAT} / P_{max})	Synchronous machine (S''_k / P_{max})
ESCR ≥ 1.0	-	-	-
0.9 ≤ ESCR < 1.0	±10 %	±7 %	33 %
0.7 ≤ ESCR < 0.9	±20 %	±13 %	66 %
ESCR < 0.7	±30 %	±20 %	100 %

The supplementary device must be connected to the grid and must be able to operate within the limits of its rated values set out in Table 1 whenever the power park module is operating at least 50 % of the rated capacity. In the case of an outage, fault or other exceptional situation, Fingrid has the right to request the supplementary device in

operation if the stable operation of the power park module at less than 50 % capacity requires the use of the supplementary device. The construction and commissioning of the supplementary device must be timed so that it is available when the power park module starts supplying active power to the grid (ION).

A GFM energy storage system must comply with the Grid Code Specifications for Grid Energy Storage Systems (SJV2024) if the energy storage system is used to provide system services, i.e. the equipment participates in the electricity or reserve market. The GFM energy storage system used as a supplementary device may be used normally in the electricity and reserve market, but market use must not limit the stabilising effect of the power plant in accordance with the minimum rated values set out in Table 1.

If ES-STATCOM equipment is used to produce system services, it is considered as an energy storage system.

If the energy storage system does not provide system services, the energy storage system can be interpreted as ES-STATCOM equipment, in which case the rated values of the ES-STATCOM equipment are applied to it (Table 1).

The ES-STATCOM must be able to supply its rated active power for at least 200 ms. The ES-STATCOM must comply with the reactive power capacity requirement of Chapter 12.2 of the SJV2024, which is defined by the rated capacity of the equipment (P_{ESTAT}). With the ES-STATCOM, it is possible to meet the power park module's reactive power capacity requirement in full or in part if it is located at the same connection point as the power park module. In this case, it must be noticed that the equipment must always be in operation when the power park module is operating above its minimum power.

3.2 Location requirements

If the GFM control is fulfilled with a supplementary device instead of the power park module's own converter units, the supplementary device must be electrically located as close as possible to the power park module's converter units. The supplementary device can be connected either

- as part of the power park module's internal electricity system.
- to the network operator’s or Fingrid’s same substation to which the power park module is connected via a radial connection.
- to the network operator’s or Fingrid’s same 110 kV transmission line to which the power park module is connected.

The principle is that a fault in a 110 kV or 400 kV line connected to Fingrid's meshed transmission system must not lead to the power park module and its supplementary device ending up in separate parts of the grid. Therefore, they cannot be located at different Fingrid substations (400 kV or 110 kV) or in such a way that one is connected to Fingrid's switchgear and the other to a 110 kV transmission line. When placing supplementary device, it must be noticed that the equipment must always be available when the power park module supplies power in accordance with the requirements of Section 3.1 .

The electrical distance between the power park module and supplementary device must not exceed 60 km. The distance must also consider the variable network topologies, which are determined by the normal (main) use situation of the network in terms of these requirements. The voltage level of the network (400 kV and 110 kV) does not affect the determination of the distance.

Figure 1 illustrates the different ways of connecting supplementary device.

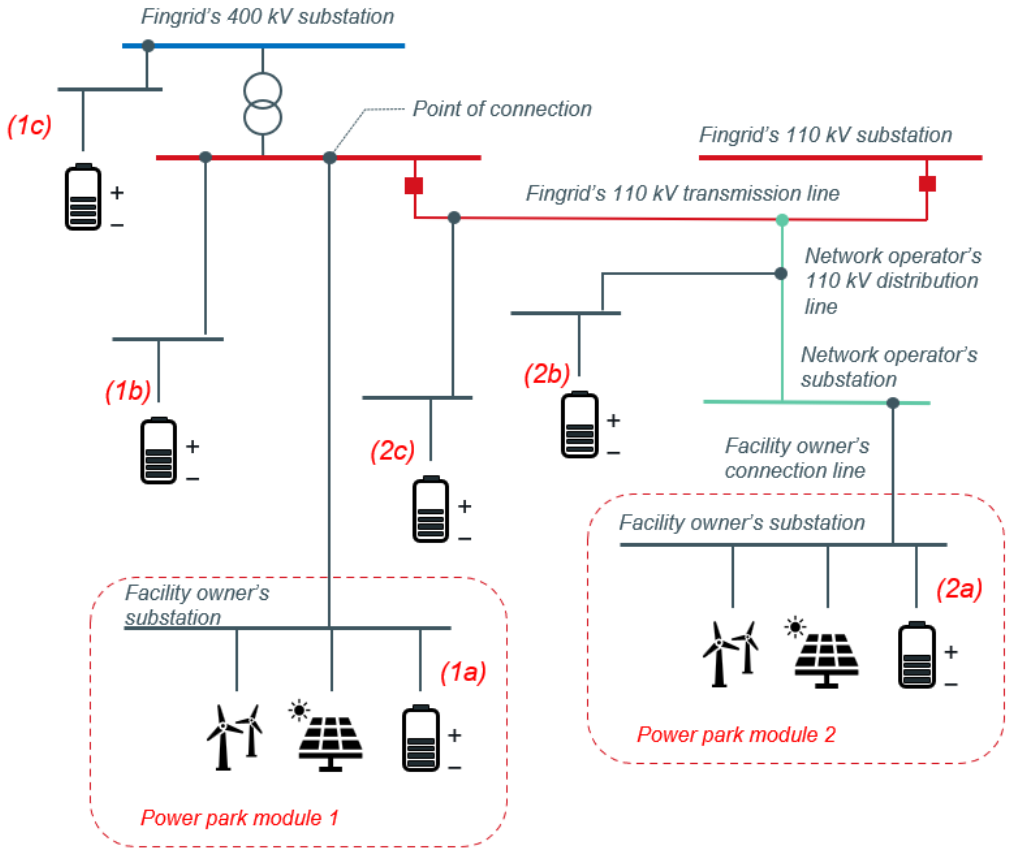


Figure 1. Examples of ways to connect a supplementary device. The connection point of power park module 1 is at Fingrid's 110 kV substation, in which case its supplementary device can be connected to the power park module (1a) or via a radial connection to the same Fingrid's substation at a voltage level of 110 kV (1b) or 400 kV (1c). The connection point of power park module 2 is at the substation of the distribution system operator connected to Fingrid's 110 kV line, in which case its supplementary device can be connected to the power park module (2a), the distribution system operator's 110 kV line/substation (2b) or Fingrid's 110 kV line (2c).

3.3 Requirements for GFM equipment

This chapter presents the requirements for GFM equipment to ensure the stable operation of a power park module and its fault ride-through capability in converter-dominated areas.

3.3.1 Implementation of GFM control for a power park module

3.3.1.1 General requirements

The GFM properties of a GFM power park module

- must be implemented in all converter connected units of the power park module.
- must be operational whenever the power park module is connected to the network. In addition, the operating mode must not change in the event of changes or disturbances in the network.
- must be operational when the power park module operates at any point within the limits of the rated capacity in production and demand mode and the reactive power capacity required for the power park module.
- must be operational in all of the power park module's active power control modes, such as constant power control and frequency control modes.
- must be operational in all of the power park module's reactive power control modes, such as constant voltage control, constant reactive power control, and constant power factor control.
- must operate in a coordinated manner at the converters' current limits so that any need to restrict the current does not result in discontinuity of the grid-forming controller function or otherwise jeopardise the stable operation of the power park module.
- must operate in a coordinated manner with the other controls affecting the power park module's active and reactive power and other top-level controls (e.g., plant-level controls in a hybrid power-generating facility) so that no adverse interactions arise between the controls.

3.3.1.2 Functional requirements

The following functional requirements apply to GFM control features:

1) Power park module's voltage source behaviour and response limitation

   a) In a stepwise phase angle change of the grid voltage, the active current of the power park module must change naturally as determined by the internal voltage source, the grid voltage and the effective impedance between them (see point 3). The response must start almost without delay, and it must resist the phase angle

change of the voltage. In this case, the device can be considered to support the angle stiffness of the system.

b) In the stepwise amplitude change of the grid voltage, the reactive current of the power park module must change naturally as determined by the internal voltage source, the grid voltage and the effective impedance between them. The response must start almost without delay, and it must resist the change in the amplitude of the voltage. In this case, the device can be considered to support the voltage stiffness of the system.

c) The response in accordance with points a and b must be visible in the terminals of the power park module's converter units within a few milliseconds of the change in the grid voltage. The control objective is to keep the voltage phasor of the internal voltage source generated by the control system approximately constant from subtransient to transient timeframe. The response must utilise the available capacity of the equipment, considering the current, power and energy limitations specified in points d, e and f.

d) The power park module's active power response is allowed to be limited based on the availability of primary energy, the current capacity of the converter units, and the power park module's inherent energy capacity. The power or current limitation must not interrupt the GFM control, cause a discontinuous change in the operating state, or jeopardise the stable operation of the power park module. The power park module must also behave as a voltage source behind the effective impedance within the available current, power, and energy limits during the limitation.

e) A power park module that does not have an energy storage or other sufficient built-in energy capacity is not required to increase the active power in accordance with point (a) when it is operating at the maximum available active power or current limit. For this purpose, the power park module is not required to reserve a continuous active power reserve. In such a case, the active power response may be limited on the basis of the available active power and current capacity, following the principles defined in point (d).

f) A power park module that does not have an energy storage or other suitable energy intake capacity is not required to draw active power from the electricity network. If the GFM response would otherwise lead to a change in the direction of active power flow, the active power response may be limited to zero in accordance with the principles defined in point d.

2) The power park module's capability to operate in an island within the energy and power limitations

a) When the voltage and frequency reference of the external power grid is lost, the power park module must establish and maintain voltage-source-like behaviour and stabilise the voltage of the island within its available current, power and energy limits.

b) The power park module must be able to supply a local load in such a way that transition to an island does not lead to an immediate loss of ability to regulate voltage or frequency.

c) The requirement applies to the immediate dynamic behaviour of the power park module after transition to an island and does not require continuous island operation capability or support of a long-term power balance.

3) Effective impedance

a) The real and imaginary parts of the power park module's effective impedance must be positive when viewed from the connection point.

b) The effective impedance of the power park module's positive sequence must not exceed 0.5 when viewed from the connection point. The reactance to resistance ratio X/R of the effective impedance must be greater than 10.

c) The effective impedance of the negative sequence must be in the same order of magnitude to the effective impedance of the positive sequence.

d) The requirements of points a–c must be met in voltage dips of different depths and voltage phase angle changes during the change, as well as at the beginning and later stages of the disturbance.

e) The effective impedance is allowed to exceed the maximum value specified in point b, at which the power park module operates in the vicinity of the current limits or reaches the current limit. However, the current limitation must be implemented in such a way that the power park module maintains its voltage source characteristics and appears as the voltage source behind the effective impedance when viewed from the connection point.

f) The effective impedance consists of the physical impedance viewed from the connection point of the power park module and the virtual impedance formed by the GFM control.

4) Stability and damping properties

a) The power park module must maintain the small signal stability at the operating points and network situations defined for it. The power park module, including its unit-level and plant-level control systems, shall not cause undamped or weakly attenuated oscillations.

b) The power park module shall not amplify frequency, voltage or power oscillation in the power system or weaken the attenuation of them. Particular attention shall be paid to the following frequency ranges examined in the dq-coordinate system:[1]

[1] The frequencies represented in the dq plane (in the coordinate system) can be represented in the abc plane relative to the nominal frequency of 50 Hz, e.g. the 1–15 Hz frequency range in the dqplane can be interpreted in the abc-plane as the frequency ranges 35–49 Hz and 51–65 Hz frequency ranges.

i) 0,2 Hz to 1,0 Hz (interpreted at the dq plane) of inter-area power oscillations

ii) 1 Hz to 15 Hz (interpreted at the dq plane) at which voltage and power oscillation associated with the interactions between converter connected equipment and the power grid may occur; and

iii) 15 Hz to 45 Hz at which resonant frequencies occur in a series-compensated network.

c) If the requirements of points a and b are not met due to the natural characteristics of the power park module or the tuning of the control parameters, the power park module must implement a separate damping control.

5) Operation with asymmetric grid voltage

a) In case of asymmetric grid voltage, the power park module shall behave, also in a negative sequence system, as a voltage source behind the effective impedance. The current of the negative sequence shall be determined by the negative sequence of the voltage and the effective impedance of the negative sequence within the available current capacity.

b) The negative sequence response is allowed to be limited on the basis of the power park module's continuous and short-term current capacity. The restriction of the negative sequence current must not interrupt the GFM control, cause a discontinuous change in the operating state or jeopardise the stable operation of the power park module. In a restriction situation, the positive and negative sequence currents must be coordinated so that the total current of the power park module remains within the limits of the current capacity of the equipment and the behaviour as a voltage source behind the effective impedance is maintained.

3.3.1.3 Stability requirements

The power park module and its plant- and unit-level controls must be designed to operate in stable manner as part of a power system, in which the proportion of converter connected power plants and converter connected consumption plants is dominant compared to the number of synchronous machines. (VJV2024, 18.2.1)

The power park module shall be able to remain connected to the electricity network during faults in the meshed network and during one- or three-phase automatic reconnections, provided that the connection point of the power park module is not in the part of the electricity network to be disconnected. The power park module shall not be disconnected and shall continue to operate in stable manner, and the operating point shall return to the operating point prior to the change, if there is a permanent stepwise phase angle change in the grid voltage, which magnitude does not exceed ±30 degrees.

3.3.2 GFM energy storage system or ES-STATCOM operating as a supplementary device

3.3.2.1 General requirements

The GFM properties of a supplementary device

- must be implemented in all converter connected units of the supplementary device.
- must be operational whenever the supplementary device is connected to the network. In addition, the operating mode must not change in the event of changes or disturbances in the network.
- must be operational when the supplementary device operates at any point within the limits of the rated capacity in production and demand mode and the reactive power capacity required for the supplementary device.
- must be operational in all of the supplementary device's active power control modes , such as constant power control and frequency control modes.
- must be operational in all of the supplementary device's reactive power control modes , such as constant voltage control, constant reactive power control, and constant power factor control.
- must operate in a coordinated manner at the converters' current limits so that any need to restrict the current does not result in discontinuity of the grid-forming controller function or otherwise jeopardise the stable operation of the supplementary device.
- must operate in a coordinated manner with the other controls affecting the supplementary device's active and reactive power and other top-level controls (e.g. plant-level controls in a hybrid power-generating facility) so that no adverse interactions arise between the controls.

3.3.2.2 Functional requirements

The following functional requirements apply to GFM control features:

1) Voltage source behaviour and response limitation of the energy storage system or ES-STATCOM

   a) In a stepwise phase angle change of the grid voltage, the active current of the energy storage system or ES-STATCOM must change naturally as determined by the internal voltage source, the grid voltage and the effective impedance between them. The response must start almost without delay, and it must resist the voltage phase angle change. In this case, the device can be considered to support the angle stiffness of the system.

b) In the stepwise amplitude change in the grid voltage, the reactive current of the energy storage system or ES-STATCOM must change naturally according to the internal voltage source, the grid voltage and the effective impedance between them. The response must start almost without delay, and it must resist the change in the amplitude of the voltage. In this case, the device can be considered to support the voltage stiffness of the system.

c) The response in accordance with points a and b must be visible on the terminals of the energy storage system or ES-STATCOM converter units within a few milliseconds of the change in the grid voltage. The control objective is to keep the voltage phasor of the internal voltage source generated by the control system approximately constant from subtransient to transient timeframe. The response must utilise the available capacity of the equipment, considering the current, power and energy limitations specified in point d.

d) The active power response of the energy storage system or ES-STATCOM is allowed to be limited based on the availability of primary energy, the current capacity of the converter units, and the plant's inherent energy capacity. The power or current limitation must not interrupt the GFM control, cause a discontinuous change in the operating state, or jeopardise the stable operation of the supplementary device. The supplementary device must also behave as a voltage source behind the effective impedance within the available current, power, and energy limits during the limitation.

2) Island capability of an energy storage system or ES-STATCOM

a) The island test evaluates the immediate voltage source behaviour of the equipment when the voltage and frequency reference created by the external power grid is lost. The equipment must stabilise the voltage of the island and respond to the active and reactive power imbalance of the island within its available current, power and energy limits.

b) When becoming islanded, the equipment must immediately change its active power based on the power imbalance between the local load and the rest of the production remaining on the island. The test must verify the equipment's capability to both supply active power to the island and take active power from the island.

c) The equipment should maintain GFM control throughout the evaluation period and behave as a voltage source behind the effective impedance. Reaching the power, energy, or current limit must not cause a discontinuous change in operating mode, interruption of GFM control, or unstable operation of the equipment.

3) Effective impedance

a) The real and imaginary parts of the effective impedance of the energy storage system or ES-STATCOM equipment must be positive when viewed from the connection point.

b) The effective impedance of the positive sequence of the energy storage system or ES-STATCOM equipment must not exceed 0.5 when viewed from the connection

point. The reactance to resistance ratio X/R of the effective impedance must be greater than 10.

c) The effective impedance of the negative sequence must be in the same order of magnitude at the vicinity to the effective impedance of the positive sequence.

d) The requirements of points a–c must be met in voltage dips of different depths and voltage phase angle changes during the change, as well as at the beginning and later stages of the disturbance.

e) The effective impedance is allowed to exceed the maximum value specified in point (b) if the energy storage system or ES-STATCOM operates in the vicinity of the current limits or reaches the current limit. However, the current limitation must be implemented in such a way that the energy storage system or ES-STATCOM maintains the voltage source characteristics and appears as the voltage source behind the effective impedance when viewed from the connection point.

f) The effective impedance consists of the physical impedance viewed from the connection point of the energy storage system or ES-STATCOM and the virtual impedance formed by the control that creates the network.

4) Stability and damping properties

a) The energy storage system or ES-STATCOM must maintain small signal stability at the operating points and network situations defined for it. The supplementary device, including its unit-level and plant-level control systems, shall not cause undamped or weakly attenuated oscillations.

b) The energy storage system or ES-STATCOM must not amplify the frequency, voltage or power fluctuations of the power system or weaken their attenuation. Particular attention shall be paid to the following frequency ranges to be considered in the dq-coordinate system[2]:

i) 0,2 Hz to 1,0 Hz (interpreted at the dq plane) of inter-area power oscillations

ii) 1 Hz to 15 Hz (interpreted at the dq plane) at which voltage and power oscillation associated with the interactions between converter connected equipment and the power grid may occur; and

iii) 15 Hz to 45 Hz at which resonant frequencies occur in a series-compensated network.

c) If the requirements of points a and b are not met due to the natural characteristics of the supplementary device or the tuning of the control parameters, the supplementary device must implement a separate damping control.

[2] The frequencies represented in the dq plane (in the coordinate system) can be represented in the abc plane relative to the nominal frequency of 50 Hz, e.g. the 1–15 Hz frequency range in the dq plane can be interpreted in the abc plane as the frequency ranges 35–49 Hz and 51–65 Hz.

5) Operation with asymmetric grid voltage

a) In case of asymmetric grid voltage, the energy storage system or ES-STATCOM must behave, also in the negative sequence system, as a voltage source behind the effective impedance. The current of the negative sequence shall be determined by the negative sequence of the voltage and the effective impedance of the negative sequence within the available current capacity.

b) The negative sequence response is allowed to be limited on the basis of the supplementary device's continuous and short-term current capacity. The restriction of the negative sequence current must not interrupt the GFM control, cause a discontinuous change in operating state, or jeopardise the stable operation of the supplementary device. In a restriction situation, the positive and negative sequence currents must be coordinated so that the total current of the supplementary device remains within the limits of the current capacity of the equipment and the behaviour of the voltage source behind the effective impedance is maintained.

3.3.2.3 Stability requirements

The supplementary device and its plant- and unit-level controls must be designed to operate in stable manner as a part of a power system in which the proportion of converter connected power plants and converter connected consumption plant is dominant compared to the number of synchronous machines. (VJV2024, 18.2.1)

The energy storage system or ES-STATCOM shall be able to remain connected to the electricity network during faults in the meshed network and during automatic one- or three-phase reconnections, provided that the connection point of the supplementary device is not in the part of the grid to be disconnected. The energy storage system or ES-STATCOM shall not be disconnected and shall continue to operate in stable manner, and the operating point shall return to the operating point prior to the change, in the event of a permanent stepwise phase angle change in the grid voltage, which magnitude does not exceed ±30 degrees.

3.3.3 Synchronous machine

A synchronous machine can be an independent synchronous condenser or a synchronous generator connected to a turbine/motor of a synchronous machine power park module by means of a fixed or openable switch.

Synchronous machine equipment must comply with the requirements of VJV2024.

A synchronous machine used as supplementary device is allowed to be used normally in the electricity and reserve markets.

With synchronous machine equipment, it is possible to meet the power park module's reactive power capacity requirement in full or in part if it is located at the same connection point as the power park module. In this case, it must be noticed that the equipment must always be in use when the power park module is operating above its minimum power.

The rated short-circuit power of the synchronous machine equipment shall be calculated based on the method specified in the IEC 60909-0 standard. The rated short-circuit power shall be fulfilled as viewed from the connection point of the synchronous machine plant. The following principles shall be followed in the calculation of the short-circuit power of the connection point:

- The calculation is performed at the nominal voltage of the connection point.
- The voltage factor for short-circuit current calculation is 1.0.
- The calculation is performed using the saturated subtransient longitudinal reactance (x_d'') of the generator and the reactance of the transformer.
- The impedances of the components of the power grid between the synchronous machine and the connection point must be considered in the calculation.

3.4 Required dynamic studies

The studies described in this chapter must be carried out using a simulation model prepared for PSCAD software that meets Fingrid's current modelling requirements. The model used must be submitted to Fingrid as part of the documentation for stage 1 of the VJV2024.

3.4.1 Dynamic studies for a GFM power park module

In addition to the dynamic studies defined in VJV2024, the studies specified in chapters 3.4.1.1–3.4.1.7 are carried out the GFM power park module. The studies must be carried out at the latest in stage 1 of the compliance monitoring process of the specifications. However, Fingrid recommends that the studies are carried out with the preliminary design values of the power park module already in stage 0 of the compliance monitoring process of the specifications, before the selection of the power park module technology and the acquisition of equipment.

3.4.1.1 Operation in the event of a voltage disturbance

The study shall describe the dynamic operation of the power park module in the event of voltage disturbances, the calculation bases for the studied disturbances 1–4 are presented in Table 2.

The voltage disturbance study should be carried out with the following assumptions:

- The short-circuit power of the connection point is assumed to be at the lower end of the normal range reported by the network operator of the connection point before the disturbance.
- The studied faults include at the connection point occurring
    I. 3-phase short circuit with no fault resistance,
    II. 2-phase short circuit with no fault resistance,

III. 2-phase short circuit with ground contact and no fault resistance, and

IV. 1-phase ground fault with no fault resistance.

- The results of the study must be compared with the protection settings of the power park module, and it must be shown that the protection does not function incorrectly in the event of a voltage disturbance.

Table 2. Initial data used in voltage disturbance study.

Initial data	Disturbance 1	Disturbance 2	Disturbance 3	Disturbance 4
Duration of voltage disturbance	200 ms	200 ms	200 ms	250 ms
Connection point voltage during disturbance	0.0 pu	0.0 pu	0.0 pu	0.25 pu
Short-circuit power of the connection point before disturbance	Normal	Normal	Normal	Normal
Short-circuit power of the connection point after disturbance	Minimum	Minimum, voltage phase angle difference +30°	Minimum, voltage phase angle difference −30°	Normal
Faults to be studied	I-IV	I	I	I

3.4.1.2 Phase angle change of grid voltage

The study shall demonstrate the capability of the power park module to remain connected to the grid and continue to operate in the event of a voltage disturbance in the grid, resulting in a grid voltage phase angle change of +30° and -30°, as specified in Chapter 3.3.1.3 .

3.4.1.3 Island operation

The island test assesses the immediate voltage source behaviour of the power park module when the voltage and frequency reference of the external power grid is lost. The power park module must stabilise the voltage of the island and supply the local load within its available current, power and energy limits. The local load and the operating point prior to the testing of the power park module must be selected in such a way that the becoming islanded does not require an increase in the available active power from a power park module without energy storage or the extraction of active power from the grid.

The island test does not verify the power park module's continuous island operation capability or its capability to maintain the island's long-term power balance. The power park module's voltage source behaviour is assessed by a three fundamental electrical cycle measurement period starting 15 ms after becoming islanded. The power park module must continue to supply the island throughout the assessment period, i.e. at least 75 ms after becoming islanded. After this, no further supply of the island is required.

3.4.1.4 Impedance scan

A dynamic impedance scan is performed for the power park module in the frequency range of 1–300 Hz. The scan is carried out from the connection point or at the converter level in a way that the scan correctly considers the operation of the GFM control. Fingrid evaluates the results of the impedance scanning against the requirements of Chapter 3.3.1 .

3.4.1.5 Voltage oscillation damping test

The voltage oscillation damping test described in Appendix 1 is performed to the GFM power park module. Fingrid will evaluate the results of the voltage oscillation damping test against the requirements of Chapter 3.3.1 .

3.4.1.6 Phase angle oscillation damping test

The phase angle oscillation damping test described in Appendix 2 is performed to the GFM power park module. Fingrid will evaluate the results of the phase angle oscillation damping test against the requirements of Chapter 3.3.1 .

3.4.1.7 Capability to operate as part of a converter-dominated system

The facility owner provides a PSCAD simulation model of the GFM power park module. Fingrid uses the simulation model to assess the power park module's capability to operate without supplementary device at the connection point without reducing the stability of the power system.

3.4.1.8 Determining the effective impedance

The effective impedance of a GFM power park module shall be determined in accordance with the principle described in Appendix 5.

3.4.2 Dynamic studies for the grid-following power park module

In this chapter, a grid-following (GFL) power park module refers to a power park module that requires supplementary device to be connected to the grid. The dynamic studies to be performed for supplementary device are defined in Chapters 3.4.3 and 3.4.4 .

The dynamic studies specified in VJV2024 are performed to the GFL power park module. If the ESCR value delivered to the power park module is 1.0 or lower, simulations shall be performed for the power park module using the ESCR test bench model. The ESCR test bench model is described in more detail in Appendix 4.

Inspections carried out with the test bench model are performed only for the GFL power park module without supplementary device.

3.4.3 Dynamic studies for the GFM energy storage system and ES-STATCOM

The dynamic studies specified in SJV2024 are performed for the GFM energy storage system and ES-STATCOM. In addition, in stage 1 of the compliance monitoring process

of the specifications, the studies specified in Chapters 3.4.3.1 to 3.4.3.4 shall be performed.

However, Fingrid recommends that the studies specified in Chapters 3.4.3.1–3.4.3.4 are carried out with preliminary design values already in stage 0 before the energy storage system or ES-STATCOM technology is selected.

3.4.3.1 Voltage oscillation damping test

- The GFM energy storage system or ES-STATCOM is required to achieve attenuation factor of less than 0.5 pu in the frequency range of 1 to 10 Hz and less than 0.9 pu in the frequency range of 0.3 to 0.5 Hz and 10 to 40 Hz (interpreted in the dq plane).
- The GFM energy storage system or ES-STATCOM is required to achieve an angle difference between 120 and 240 degrees across the entire frequency band under consideration from 0.3 Hz to 40 Hz (interpreted in the dq plane).
- The voltage oscillation damping test is described in more detail in Appendix 1.

3.4.3.2 Phase angle oscillation damping test

- The GFM energy storage system or ES-STATCOM is required to achieve attenuation factor of less than 0.9 pu across the entire frequency band considered.
- The GFM energy storage system or ES-STATCOM is required to achieve an angle difference between 120 and 240 degrees over the entire frequency band under consideration.
- The phase angle oscillation damping test is described in more detail in Appendix 2.

3.4.3.3 GFM test bench

- On the GFM test bench, the energy storage system or ES-STATCOM is required to demonstrate the capability to prevent wind power plants from disconnecting in the event of a fault by supporting the voltage phase angle and reducing the overvoltage after the failure. If the wind power plant is disconnected from the grid during a fault or when recovering from a fault, the required stabilisation capability of the supplementary device is not fulfilled.
- The GFM test bench is described in more detail in Appendix 3.

3.4.3.4 Determining the effective impedance

- The effective impedance of the GFM energy storage system or ES-STATCOM shall meet the functional requirements of Chapter 3.3.2.2 .

- The effective impedance of the GFM energy storage system or ES-STATCOM shall be determined in accordance with the principle described in Appendix 5.

3.4.4 Dynamic studies for the synchronous machine

A voltage disturbance study must be performed for the synchronous machine in accordance with VJV2024 Chapter 10.5.4.

4 Instrumentation and real-time data exchange

4.1 Instrumentation

The supplementary device to be placed in connection with the power park module shall be equipped with a continuous recorder system in accordance with Chapter 9.5 of the VJV2024, which measures the current and voltage supplied by the supplementary device so that the response of the supplementary device can be verified separately from the response of the rest of the power park module.

4.2 Real-time data exchange

Fingrid must be provided with information on the availability of the supplementary device to be placed in connection with the power park module:

- "in operation" information that is generated in the equipment’s automation system is provided from ES-STATCOM.
- Generator circuit breaker status information is provided from the synchronous machine.

In any case, Fingrid will be provided with active and reactive power data from the energy storage system, so there is no need for separate availability information.

5 Documents and simulation models to be delivered

In stage 1 of the power park module compliance monitoring process of the specifications, the following supplementary device documentation must be submitted:

- technical documentation which scope corresponds to the scope specified in the VJV2024 to be delivered from the power park module.
- simulation models for PSCAD and PSSE software in accordance with Fingrid's modelling guidelines.

If the supplementary device is implemented as an energy storage system or ES-STATCOM, the scope of documentation for the supplementary device is in accordance with SJV2024.

In addition, the documentation must include:

- a detailed system description demonstrating compliance with the requirements of Chapter 3.3 .
- an open-format report on the dynamic studies in Chapter 3.4 . The results of the studies can be used in the above-mentioned system description to justify the fulfilment of the requirements.

6 Commissioning tests

The power park module commissioning tests shall be carried out, where applicable, to the extent specified in VJV2024. If the supplementary device is an energy storage system or ES-STATCOM, the commissioning tests and their reporting shall be carried out, where applicable, to the extent specified in SJV2024.

With Fingrid's consent, continuous monitoring based on a continuous recording system (Chapter 3) can be used in the verification of GFM features (incl. verification of modelling data) if it is not possible to verify the response by tests.

A commissioning test plan and a commissioning report in accordance with VJV2024 must be submitted from the commissioning tests in stage 2 of the compliance monitoring process of the specifications.

Appendix 1 / Voltage oscillation damping test

- In the test, voltage oscillation is fed from the background network at frequencies 0.3–0.5 Hz and in the frequency range 1–40 Hz. In the test, a voltage disturbance $\Delta V_{scr}(f_k)$ is fed behind the source impedance at the frequency f_k, and the voltage component of the same frequency is measured at the connection point $\Delta V_{poc}(f_k)$. In addition, the reactive power supplied by the plant to the connection point is measured $\Delta Q_{poc}(f_k)$. The results evaluate the following parameters:

    i. The attenuation factor describes the amplifying or dampening effect of the plant on voltage oscillation. The attenuation factor is calculated according to the formula $UampF(k) = \frac{|V_{\mathrm{poc}}(f_k)|}{|V_{\mathrm{scr}}(f_k)|}$. The plant is considered to damp voltage oscillation at the frequency f_k if the attenuation factor obtains a value of 1.0 or less.

    ii. The angle difference describes the angle difference between the voltage and the supplied reactive power. The angle difference between the voltage and the reactive power is attenuating the voltage oscillation if the angle difference is between 90 and 270 degrees.

    iii. The reactive power response describes the magnitude of the reactive power supplied by the plant in relation to the voltage change. The reactive power response is calculated according to the formula $QrespF(k) = \frac{|Q_{\mathrm{poc}}(f_k)|}{|V_{\mathrm{poc}}(f_k)|}$.

- The test is performed with a background network value of SCR of 2 and X/R of 10. In the case of an energy storage system, the test is performed at maximum discharge, maximum charge and zero power. The active power of ES-STATCOM is set to zero initially.

Appendix 2 / Phase angle oscillation damping test

- In the test, the voltage phase angle oscillation at frequencies 0.3–0.5 Hz and in the frequency range of 1–40 Hz is supplied from the background network. In the test, a phase angle disturbance $\Delta ph(V_{scr}(f_k))$ is fed behind the source impedance at the frequency f_k, and the phase angle component of the same frequency is measured at the connection point $\Delta ph(V_{poc}(f_k))$. In addition, the active power supplied by the plant to the connection point is measured $\Delta P_{poc}(f_k)$. The results evaluate the following parameters:

    i. The attenuation factor describes the amplifying or dampening effect of the plant on phase angle oscillation. The attenuation factor is calculated according to the formula $\theta ampF(k) = \frac{ph(V_{\mathrm{poc}}(f_{\mathrm{k}}))}{ph(V_{\mathrm{scr}}(f_{\mathrm{k}}))}$. The plant is considered to damp the phase angle oscillation at the frequency f_k if the attenuation factor obtains a value of 1.0 or less.

    ii. The angle difference describes the angle difference between the voltage phase angle and the active power supplied by the plant. The angle difference between the voltage phase angle and the active power is attenuating the phase angle oscillation if the angle difference is between 90 and 270 degrees.

    iii. The active power response describes the magnitude of the active power supplied by the plant in relation to the phase angle change. The active power response is calculated according to the formula $PrespF(k) = \frac{|P_{\mathrm{poc}}(f_{\mathrm{k}})|}{ph(V_{\mathrm{poc}}(f_{\mathrm{k}}))}$.

- The test is performed with a background network value of SCR 2 and X/R of 10. The active power of the energy storage system and ES-STATCOM is set to zero at the starting point of the test. The energy storage system and ES-STATCOM are in the test with voltage control at slope of 4 % and the voltage of the background network is the nominal voltage of the connection point.

Appendix 3 / GFM test bench study for supplementary device

The GFM test bench demonstrates the capability of the supplementary device to support the operation of a wind power plant consisting of GFL converters in the event of a fault. Fingrid will provide a test bench and more detailed instructions on how to perform the test to the facility owner.

The test bench is a PSCAD model with seven generic wind power plant models connected to it. In the test bench, the facility owner adds an energy storage system or ES-STATCOM next to each wind power plant. The size of the energy storage system or ES-STATCOM is scaled in the test bench according to the instructions so that its size is 30 % of the size of the generic wind power plant.

The test bench includes two tests to verify the required capability of the supplementary device to support the GFL converters. For the test bench’s generic wind power plants have been set limit values for the amount of AC voltage at the connection point and for the energy accumulated in the converter's DC link. If the limit values are exceeded, the wind power plant will be disconnected from the grid, and the required capability from a supplementary device will not be fulfilled. The supplementary device must be able to keep the connection point voltage and the energy accumulated in the DC link below the limit values.

In the test, the active power of the energy storage system and ES-STATCOM is set to zero at the starting point of the test.

Appendix 4 / ESCR test bench study for a GFL power park module

The ESCR test bench model is used to test the capability of a GFL plant to operate as part of a converter-dominated system. Fingrid will provide a test bench and more detailed instructions on how to perform the test to the facility owner.

The test bench is a PSCAD model with six substations in which is going to be connected a total of seven simulation models of the same power park module. In the simulations, all power park modules must be able to cope with a grid fault and subsequent disconnection of a specified transmission line without disconnecting from the grid or generating weakly attenuated oscillation.

Appendix 5 / Determination of effective impedance

Disturbances to be tested

The effective impedance and its X/R-ratio should be determined for the GFM converter connected power park module, energy storage system or ES-STATCOM in symmetrical and asymmetric voltage dips of different depths and voltage phase angle changes.

The purpose of the assay is to describe the voltage source behaviour observed at the connection point of the plant and the change in behaviour from the initial phase of the disturbance to the later transient phase.

The effective impedance is determined at least in the following cases:

a) three-phase voltage dips with a remaining voltage of 0 % to 90 % of the nominal voltage in 10 percentage point increments.

b) single-phase voltage dips with a remaining voltage of the faulty phase between 0 % and 90 % of the nominal voltage in 10 percentage point increments.

c) voltage phase angle changes between 5 and 30 degrees in 5-degree increments in both positive and negative directions.

Voltage dips are implemented without a deliberate voltage phase angle change. Voltage phase angle changes are implemented without a deliberate change in the voltage amplitude.

The tests are carried out at different active and reactive power operating points so that the plant's behaviour is assessed at least at the lowest, highest and corresponding normal operating power. It is recommended that the test is carried out using the PSCAD model.

Observation periods and time windows

The effective impedance is determined in the following steps that can be calculated from the start of the disturbance:

a) the response during disturbance, which is determined from the first reliably determinable peak current or power response occurring after the disturbance, but no later than 10 ms after the start of the disturbance.

b) early transient response, which is determined 30 ms after the start of the disturbance.

c) a later transient response, which is determined 100 ms after the start of the disturbance.

The values of points b and c shall be determined from a time window defined around the reference time point instead of a single measurement sample. The length of the time window shall be sufficient to reliably determine the base-frequency voltage and current

component but shall not hide substantial changes in the effective impedance over the period under consideration.

The response during disturbance shall be analysed using the response determined on the basis of phase-specific momentary values or voltage and current vectors represented in a stationary coordinate system. The method of averaging over the entire period shall not be used if the averaging hides the activation of the response or current limitation during the first 10 ms.

Effective Impedance Calculation

The effective impedance is determined for the positive and negative sequence as the ratio of the measured changes in the complex voltage and current components before the event and at the time of observation:

$$\underline{Z}_{\mathrm{eff,k}}(t) = -\frac{\Delta \underline{U}_{\mathrm{k}}(t)}{\Delta \underline{I}_{\mathrm{k}}(t)},\ k \in \{1, 2\},$$

where k = 1 means a positive, and k = 2 a negative sequence. The positive direction of the current is from the equipment to the network.

The impedance's resistance, reactance, absolute value and X/R-ratio are determined as follows:

$$R_{\mathrm{eff,k}} = \mathrm{Re}\{\underline{Z}_{\mathrm{eff,k}}\},\ X_{\mathrm{eff,k}} = \mathrm{Im}\{\underline{Z}_{\mathrm{eff,k}}\},$$

$$Z_{\mathrm{eff,k}} = |\ \underline{Z}_{\mathrm{eff,k}}\ |,\ \frac{X}{R} = \frac{X_{\mathrm{eff,k}}}{R_{\mathrm{eff,k}}}.$$

The effective impedance of the positive sequence is determined in all the events to be tested, and the effective impedance of the negative sequence in asymmetric voltage dips. In the case of voltage phase angle changes, the calculation is done with complex indicators.

References

[1] Managing converter stability through grid forming
(URL: https://www.fingrid.fi/globalassets/dokumentit/fi/palvelut/kulutuksen-ja-tuotannon-liittaminen-kantaverkkoon/white-paper---managing-converter-stability-through-grid-forming.pdf)