Specific Study Requirements for Grid Energy Storage Systems

1 Scope of application

This document defines *Specific Study Requirements* for type D battery energy storage systems (BESS) connected to specific locations in Fingrid's network where use of grid forming controls (GFM) is seen as necessary. These requirements are also applicable for other networks connected to Fingrid's network.

The requirements are set according to the Specific Study Requirements defined in Grid Code Specifications for Grid Energy Storage Systems (SJV2019, Chapter 5, [1]). According to the Grid Code, the Connectee shall request from Fingrid the assessment of a need for specific study during the preliminary planning stage of the BESS so that the requirements are considered in the design and procurement of equipment.

The specific study requirements are always assessed separately for each type D battery energy storage system and if seen as necessary, can be supplemented with additional project specific requirements beyond the scope presented in this document.

2 Introduction

Currently, large number of BESS are planned to connect to the transmission grid in Finland. Studies have shown that grid following (GFL) inverter-based resources (IBR) are not able to operate in stable manner when the share of the converters is increasing in the future. Solution for operating the inverters in stable manner is to use grid forming control. Grid forming IBRs are needed to compensate 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 majority of the wind power plants are located. In these regions, connection of more GFL inverters is not possible before grid strengthening measures as it would endanger the stable operation of the power system.

By common definition, a grid forming resource shall be able to self-synchronize, operate in stand-alone mode and provide synchronization services which include synchronizing power, system strength, fault current and virtual inertial response. More detailed description of the properties of GFM can be found e.g. in [2] or [3]. Globally, several GFM BESS projects have been successfully integrated to the bulk power systems (BPS) to provide instantaneous frequency and voltage support which are not possible for GFL IBRs. The use of GFM technology in the Finnish power system can be seen beneficial as it helps to preserve the overall system security and improves connectivity of new IBRs.

All inverter-based energy storage systems connected to Finnish power system must comply with The Grid Code Specifications for Grid Energy Storage Systems SJV2019 [1]. The grid code SJV2019 has been originally created to set the requirements for GFL inverters and consequently the requirements for emerging grid forming (GFM) technology are not addressed in the grid code. This document describes functional requirements, simulation studies and field tests to ensure and prove that the GFM control is implemented in such a way that it supports the stable operation of the inverter dominated grid and that the unique characteristics of GFM are utilized in an appropriate way.

3 Requirements

Basic requirements for grid energy storage systems are presented in SJV2019. The requirements presented in this document for GFM BESS supplement, and in case of conflict, replace the requirements of SJV2019.

The requirements for GFM BESS are divided in

- functional requirements (3.1)
- active power control and frequency control requirements (3.2)
- voltage control and reactive power control requirements (3.3)
- modelling requirements (3.4) and
- test requirements (3.5)

3.1 Functional requirements

The rated capacity in production mode, $P_{max,p}$, and the rated capacity in the demand mode, $P_{max,d}$, of the GFM BESS at the Connection Point is defined in the Connection Agreement.

As required in SJV2019/12.2.1, the reactive power capacity of the GFM BESS shall be at least +/-0.33 x $P_{max,p}$. The reactive power capacity requirement shall be fulfilled at the high voltage terminals of the main transformer of the BESS plant which is typically at 110 kV. For a hybrid power plant consisting of e.g. of a wind power plant and BESS that share the same MV bus, the reactive power capacity of the BESS is defined separately by Fingrid.

The converters and the battery of the GFM BESS shall provide GFM operational characteristics up to a rated current. The current shall not be artificially limited below the true capability of the equipment.

All the functional specifications listed in this chapter are applicable when the GFM BESS is within its limits of the energy source behind the inverter and the equipment ratings of the inverter. These functional specifications do not impose any requirements for magnitude of current beyond equipment ratings.

The operation when the GFM BESS is reaching the current limit shall be carefully coordinated. If current limiting is required, stability and grid support must be maintained.

GFM BESS shall continue providing GFM operational characteristics even at its highest and lowest allowable state of charge (SoC).

Whenever connected to the network, the GFM BESS shall always operate in GFM mode and not to operate in GFL mode.

In addition to the requirements presented in SJV2019, the following performance characteristics are required from GFM BESS:

1. GFM-specific voltage and frequency support: GFM shall provide autonomous, near-instantaneous frequency and voltage support by maintaining a nearly constant internal voltage phasor in the sub-transient time frame, including:

    a. Phase jump performance: GFM shall resist near-instantaneous voltage phase angle changes by providing appropriate levels of active and reactive power output in the sub-transient time frame.

    b. System strength: GFM shall improve the strength of the local network by resisting the change in voltage in the sub-transient time frame

    Indicative response times

    i. Initial response within few milliseconds

    ii. Full response < 10 ms

2. Seamless transition between islanded and grid-connected operation is required: GFM shall be able to seamlessly respond based only on its local measurements to changes from a grid connected situation to an islanded situation and reconnect back again.

    a. In here, islanded operation presents a situation where a larger part of the grid including the GFM BESS, loads and possibly other generating facilities is unexpectedly disconnected from the main grid, continues operation if balance of production and loads matches and is eventually connected back to synchronous operation with rest of the system. No specific synchronization equipment is required from the GFM BESS to reconnect the islanded part of the grid. This will be done by the grid operator using a synchronizer controlling a breaker of the main grid.

    b. GFM BESS shall continue to help maintain grid nominal voltage and frequency up to its equipment capabilities.

    c. Beyond the sub-transient time frame, GFM BESS shall adjust its power output in consent (utilizing droop) with other resources to reach a new, stable operating point

    d. GFM BESS shall be able to stably operate through and following the disconnection of the last synchronous machine in its portion of the power grid when the power balance is reachable with the equipment capability and within the normal voltage and frequency operating range.

3. Positive damping: GFM shall present a positive resistance to the grid within frequency ranges 0–47 Hz and 53-250 Hz to prevent adverse interactions.
    a. It is especially important that the GFM shall not reduce damping of 0.2-0.5 Hz interarea oscillation modes.
    b. Separate damping circuit is not required if the GFM BESS has inherent capabilities to provide positive damping throughout the given frequency range.
4. Voltage balancing: GFM shall provide a closed loop path for unbalanced current to flow
    a. GFM shall present negative sequence current to ensure that its internally generated voltage remains balanced during normal operation and disturbances

3.2 Additions to active power control and frequency control requirements

The GFM control shall be always enabled regardless of the selected control mode such as constant active power control mode or frequency droop control mode (FSM).

If the BESS does not participate in the frequency containment reserve power market (FCR-N), droop-based FSM control mode is inactive by default and the BESS is operated in constant active power control mode. However, as required in SJV2019, LSFM-O (11.1.2) and LFSM-U (11.3.3.4) shall be always active and provide droop-based response also in case of island operation.

Isochronous island operation where GFM BESS is operating as master with constant frequency reference is not required. Consequently, no external control signal for switching from frequency droop control mode to isochronous operation is delivered to GFM BESS.

The shift from the initial GFM response to system state changes (presented in Chapter 3.1) to the continuous operating set point given by the active power control or frequency control of the GFM BESS shall be smooth, i.e. non-stepwise and well-damped. Also, the response to mode change shall be smooth.

If the GFM BESS is part of a hybrid power plant, the controls shall be carefully co-ordinated with the plant-level controls affecting active power so that any adverse interaction is avoided.

3.3 Additions to voltage control and reactive power control requirements

As required in SJV2019/13.2.1, the primary operation mode of GFM BESS is voltage control with adjustable droop (slope).

The GFM control shall be always enabled regardless of the selected control mode such as constant reactive power mode, power factor mode or voltage droop (slope) control mode.

The shift from the initial GFM response to system state changes (presented in Chapter 3.1) to the continuous operating set point given by the reactive power control or voltage droop control of the GFM BESS shall be smooth, i.e. non-stepwise and well-damped. Also, the response to control mode change (e.g. from voltage droop control to constant reactive power control) shall be smooth without stepwise change or oscillation.

At the beginning of the design process of the GFM BESS, the Connectee shall request from Fingrid (query submitted to vikavirrat@fingrid.fi) necessary technical information of the background network. Fingrid delivers to the Connectees grid impedance values and also so-called ESCR and VCSCR values:

- The grid impedance values (R+jX) and corresponding fault current level are used for dimensioning of equipment as well as calculation of traditional grid SCR level. Fingrid will deliver at least the values for “normal”, “minimum” and “maximum” scenarios and possibly an estimate of the future levels.
- VCSCR (Voltage Controller Short-Circuit Ratio) value is calculated at the high voltage bus, where voltage is measured for the plant-level voltage controller. VCSCR value is calculated in N-0 situation, that is, for intact grid. VCSCR value is used for plant-level voltage controller tuning.
- ESCR value is calculated at the medium voltage level. ESCR value is calculated in N-1 situation (after a fault) where the ESCR is at the lowest. This value is for evaluating the stability of the plant.
- more information can be found in [6]. The up-to-date instruction will be delivered to the Connectee by Fingrid along with the VCSCR/ESCR values.

The GFM controls shall be carefully coordinated with any other voltage or reactive power based controls affecting the GFM BESS so that any adverse interaction is avoided. This includes, for example,

- the plant-level controls such as the HV bus voltage droop control (tuned based on the VCSCR value) and
- controls of possible other parallel power generating modules of a hybrid power plant such as GFL based WPP or PV plant.

3.4 Additions to modelling requirements

A dynamic simulation model of the GFM BESS shall be prepared for PSCAD and PSS/E programs and delivered to Fingrid. Detailed requirements for the simulation models are presented in [4]. In case of a hybrid power plant (e.g. wind power plant and GFM BESS), all plant equipment and their controls have to be included in the same model.

The Connectee shall perform the simulation studies presented in Table 1. Possible need for additional simulation studies (e.g. in case of a hybrid power plant) shall be agreed separately with Fingrid in the design phase.

The results of the simulation studies are presented in a study report delivered to Fingrid along with the models no later than six months before the planned commissioning of the GFM BESS (active power supply to grid begins).

All simulations are performed in GFM operation mode in different state of charge (SoC) and active/reactive power levels as specified in Table 1. If not specified otherwise in Table 1, the plant-level control of the GFM BESS shall operate on voltage droop control (droop setting 4%) and constant active power control.

In the simulations, the GFM BESS shall present the GFM capabilities required in Chapter 3. Further acceptance criteria for each simulation, if applicable, is defined in Table 1.

Description of operating points:

A1 - SoC at energy buffer minimum level (i.e. 5 % where the battery can still supply power), P = 0 MW, Q = 0 Mvar

B1 - SoC at 50 %, $P = P_{max,p}$, $Q = Q_{cap\text{-}max}$

B2 – SoC at 50 %, P = 0 MW, Q = 0 Mvar

B3 - SoC at 50 %, $P = P_{max,p}$, $Q = Q_{ind\text{-}max}$

B4 – SoC at 50 %, $P = P_{max,p}$, Q = 0 Mvar

B5 – SoC at 50 %, $P = P_{max,d}$, Q = 0 Mvar

C1 – SoC at energy buffer maximum level (i.e. 100 %), P = 0 MW, Q = 0 Mvar

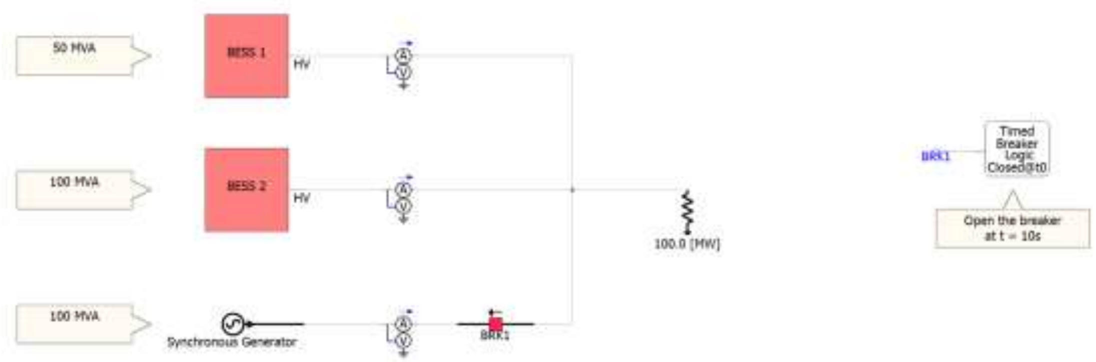
Table 1. List of required simulation studies

	Simulation number	Description	Simulation software	Operation point
Step change in voltage from network side	1.1	Voltage magnitude change ±0.02 pu, background network acc. to VCSCR level. Acceptance criteria: see, ref. [6], rise time (0-90%) of the plant-level voltage control shall be 1±0.1s.	PSCAD + PSS/E	B2
	1.2	Voltage magnitude change ±0.1 pu, carried out at ESCR and maximum SCR level	PSCAD + PSS/E	A1, B1-5, C1
	1.3	Voltage angle change up to ±30°, carried out at ESCR and maximum SCR level	PSCAD + PSS/E	A1, B1-5, C1
Balanced and unbalanced faults at the connection point	2. 1	200 ms 3-phase fault, different grid SCR level before and after the fault Acceptance criteria: this simulation will cover the FRT study of SJV2019 / 10.5.3	PSCAD + PSS/E	A1, B1-5, C1
	2.2	250 ms 3-phase fault with 0.25 pu residual voltage Acceptance criteria: this simulation will cover the FRT study of SJV2019 / 10.5.3	PSCAD + PSS/E	B2
	2.3	200 ms L-G fault Acceptance criteria: simulation is for information only	PSCAD	B2
	2.4	250 ms L-G fault with 0.25 pu residual voltage Acceptance criteria: simulation is for information only	PSCAD	B2
Consecutive faults	3.1	Two 100 ms 3-phase faults with: 110 kV: 0.6 s between faults 400 kV: 2.4 s between faults Acceptance criteria: the BESS shall ride through the faults without disconnection (SJV2019/10.5.2)	PSCAD	B2
	3.2	Two 100 ms 1-phase faults with: 110 kV: 0.6 s between faults 400 kV: 2.4 s between faults Acceptance criteria: the BESS shall ride through the faults without disconnection (SJV2019/10.5.2)	PSCAD	B2
Combination of fault and voltage magnitude and phase change	4.1	100 ms 3-phase fault and voltage magnitude change from 1 pu to 0.9 pu and phase jump +20° Acceptance criteria: the BESS shall ride through the event	PSCAD	B2

	4.2	100 ms L-G fault and voltage magnitude change from 1 pu to 0.9 pu and phase jump +20° and after 2.4 s voltage magnitude change back to 1 pu and phase jump -20° Acceptance criteria: simulation is for information only	PSCAD	B2
Over voltage ride-through	5.1	Voltage at connection point 1.6 pu for 2 ms, then 1.25 pu for 1 s Acceptance criteria: simulation is for information only	PSCAD	B2
Frequency disturbance	6.1	Operation of FSM, LFSM-U and LFSM-O. Acceptance criteria: Stacked operation of the functions having their own, different droop settings shall be demonstrated. Frequency ramp: 50…51…50…49Hz, RoCoF 0.1Hz/s.	PSCAD + PSS/E	B2
	6.2	Step change from 50 to 49.5Hz Acceptance criteria: simulation is for information only	PSCAD	B2
	6.3	Fast frequency ramp sequence test between 50…49.0…50Hz, RoCoF 0.24Hz/s.	PSCAD	B2
	6.4	Frequency ramp from 50 to 49.0Hz, RoCoF 2.0 Hz/s	PSCAD	B2
Control system simulations	7.1	Active power dispatch command step change	PSCAD	B2
	7.2	Reactive power dispatch command step change	PSCAD	B2
	7.3	Voltage droop control voltage setpoint change	PSCAD	B2
	7.4	Voltage control change from voltage droop to reactive power control	PSCAD	B2
Loss of last synchronous generator	8.1	Loss of last synchronous generator in test network grid model of Figure 1. In the test, GFM BESS 1, GFM BESS 2 and synchronous generator supply a fixed load. The synchronous generator is switched off and consequently the load is divided by GFM BESS 1 and 2. The size of GFM BESS 2 shall be equal the project specific size of the BESS (in MVAs) and GFM BESS 1 and the synchronous generator shall be scaled accordingly.	PSCAD	B2
Interarea oscillations	9.1	Inject 0.2-0.5 Hz voltage oscillations to the PCC Acceptance criteria: the BESS shall provide positive damping to the oscillation	PSCAD	B2

Dynamic impedance scan	10.1	Present the converter impedance characteristics in frequency range of 1-250 Hz Acceptance criteria: the BESS shall provide positive resistance through the frequency range.	PSCAD	A1, B1-5, C1
Unbalanced operation	11.1	Negative sequence current injection in 1-phase voltage unbalance of 3% x Un	PSCAD	B2

Figure 1. Test network for simulation scenario 8.1, "Loss of last synchronous generator". In this example scenario, the size of the GFM BESS to be connected is 100 MVA which is equal to the size of the synchronous generator.



For the simulations, at minimum the following quantities shall be plotted:

- PCC: U_{rms}, I_{rms}, P, Q, I_{abc}, U_{abc}, angle (deg)
- Inverter level: U_{rms}, I_{rms}, I_{abc}, U_{abc}, I_d, I_q

3.5 Additions to test requirements

3.5.1 Type and factory tests

A report of the hardware type tests performed for GFM control shall be delivered as part of the SJV2019 Stage 1 documentation (prior to ION).

Fingrid preserves the right to participate in the type and factory tests of the GFM BESS performed for the equipment to be delivered.

3.5.2 Site tests

In addition to the site tests required in SJV2019 Chapter 14.3.4, following additional tests shall be performed:

1. Phase jump test
    - a change in voltage magnitude and phase is introduced by changing grid topology (e.g. disconnection of a line) in the Main Grid by Fingrid or the DSO.
    - Acceptance criteria: the GFM BESS is required to perform as defined in Chapters 3.1, 3.2 and 3.3 of this document. The PSCAD and the PSS/E models shall be validated by repeating the test with a corresponding simulation scenario.
2. Island operation test
    - An upstream 110 kV breaker is opened (no position indication sent to GFM BESS). Consequently, the GFM BESS is disconnected to supply a small or moderate load, e.g. the house load of the power plant. After several minutes, the islanded grid is connected back to main grid as the breaker is closed.
    - In case of a hybrid power plant, the test shall be coordinated with rest of the power plant. The details of the test shall be agreed with Fingrid during the design stage.
    - Acceptance criteria: the GFM BESS is required to perform as defined in Chapters 3.1, 3.2 and 3.3 of this document. The purpose of the test is to show that the GFM BESS can continue normal operation when the connection to the main grid is lost. The PSCAD and the PSS/E model shall be validated by repeating the test with a corresponding simulation scenario.
3. Measurement of power quality
    - Power quality parameters as presented in IEC 61000-4-30 chapter 5, shall be measured and reported according to standard IEC 61000-4-30 Class A. Measurement device shall use three phase measurement for voltage and current. Measurements are performed at 1) inverter terminal voltage level, 2) MV bus and 3) HV bus.
    - Acceptance criteria: Measurements inside the power plant (LV, MV) are done for information only. Maximum levels on HV side (at 110kV) are defined in [5].

4. Monitoring period after the grid code tests

    - After completing of the other grid code tests, the response of the GFM BESS to major grid events is monitored for at least 30 days

    - During the monitoring, the phase currents and voltages of the high-voltage side of the power plant transformer(s) are measured. Active and reactive power and frequency are calculated from the measurements. The sampling frequency of the measuring devices used shall be at least 1 kHz and the recording frequency shall be at least 50 Hz. Existing recorders of the power plant can be used for monitoring if they are suitable for continuous measurement.

    - At the end of the monitoring period, the response is evaluated and reported. The purpose of the report is to show that GFM control works as designed and fulfills the requirements presented in this document. The simulation models shall be validated based on the most significant disturbance/event captured during the monitoring period. Validation is performed by comparing the response of the PSCAD and PSS/E models to the actual measured event (playback). The event used for validation shall be selected with Fingrid and the results of the validation shall be included in the monitoring report.

4 References

[1] The Grid Code Specifications for Grid Energy Storage Systems SJV2019, Fingrid 2019, available online: https://www.fingrid.fi/globalassets/dokumentit/en/customers/grid-connection/grid-energy-storage-systems-sjv2019.pdf. (referred: 21.6.2023)

[2] NERC, White Paper Grid Forming Technology, available online: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_Grid_Forming_Technology.pdf (referred: 21.6.2023)

[3] Unifi Consortium, Specifications for Grid-forming inverter-based resources: version 1, available online: https://drive.google.com/file/d/19YRpERnsssEJ62H_Tb0edtxHrZI37ZkK/view (referred: 21.6.2023)

[4] Fingrid, Modelling Instruction for PSS/E and PSCAD models, available online: https://www.fingrid.fi/globalassets/dokumentit/fi/palvelut/kulutuksen-ja-tuotannon-liittaminen-kantaverkkoon/modelling-instruction-for-psse-and-pscad-models.pdf (referred: 21.6.2023)

[5] Power Quality in Fingrid's 110kV grid, available online: https://www.fingrid.fi/globalassets/dokumentit/en/customers/grid-connection/20150911_110-kv_verkon_sahkonlaatu_en.pdf (referred: 21.6.2023)

[6] Guidance on ESCR values and voltage control tuning of converter connected generation, available online: https://www.fingrid.fi/globalassets/dokumentit/fi/palvelut/kulutuksen-ja-tuotannon-liittaminen-kantaverkkoon/guidance-on-escr-values-and-voltage-control-tuning-of-converter-connected-generation.pdf, 1.2.2023 (referred: 21.6.2023)