APPENDIX 1.B

REQUIREMENTS FOR GENERATORS (RFG) – SIMULATION MODEL REQUIREMENTS

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This memo presents Energinet's simulation model requirements for the connection of generation facilities. It is included as a background memo in connection with the implementation of EU regulation 2016/631, *Requirements for Generators* (RfG) [1], and consequently deals with requirements for synchronous generation facilities and asynchronous (onshore and offshore) generation facilities, cf. the definitions of these.

This memo describes:

- Functional requirements for stipulated simulation models.
- Requirements for structural design and implementation of stipulated simulation models.
- Documentation requirements for stipulated simulation models.
- Accuracy requirements for stipulated simulation models.
- Verification requirements for stipulated simulation models.

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1. Background

Due to the ongoing transition of the electricity system, with conventional generation facilities gradually being phased out and replaced by more complex generation facilities, the transmission system operator requires greater insight into these new facilities' structural design and their systemic impact on the public electricity supply grid.

For analytical purposes related to planning and operation of the public electricity supply grid, the transmission system operator must be able to do grid and system analyses, for example when connecting new generation facilities to the grid. This requires up-to-date and accurate simulation models of grid-connected demand and generation facilities.

Simulation models are used to analyse the transmission and distribution grids' static and dynamic states, including voltage, frequency and rotor angle stability, short-circuit ratios, transient phenomena and harmonic conditions.

The statutory authority to set requirements for simulation models is provided in [1]. When setting requirements, the transmission system operator refers to international standards whenever possible to ensure that definitions and procedures used are in line with these.

2. General simulation model requirements

The facility owner must submit simulation models to the transmission system operator [1]. These simulation models must properly reflect the generation facility's steady-state and quasi-steady state properties. The facility owner must also submit a dynamic simulation model (RMS (root-mean-square) model) and a transient simulation model (EMT (electro-mechanical transient) model) to the transmission system operator for time domain analyses. In addition, the facility owner must submit a harmonic simulation model for analysis of the harmonic state of the public electricity supply grid, including the generation facility's contribution to harmonic emissions in the point of connection.

Please see Table 1 for information on requirements for simulation models and delivery scope for the respective types of generation facilities [1]. The facility owner must ensure that models are delivered on time under current procedures for grid connection of generation facilities and other provisions in the regulation.

Generation facility types	Synchronous generation facilities	Asynchronous generation facilities
Type A	No requirement for simulation model	No requirement for simulation model
Type B	No requirement for simulation model	No requirement for simulation model
Type C	Static simulation model RMS simulation model	Static simulation model RMS simulation model
Type D	Static simulation model RMS simulation model	Static simulation model RMS simulation model EMT simulation model Harmonic simulation model

Table 1 Simulation model requirements for specific generation facility types.

The facility owner must ensure that simulation models are verified with the results of the compliance tests defined [1] as well as relevant test and verification standards and must submit the required documentation hereof.

If the generation facility incorporates external components, for example to comply with grid connection requirements or for the delivery of commercial ancillary services, the simulation model must include the necessary representation of these components applicable for all required model types.

From the generation facility's design phase to the time of issue of the final operational notification (FON), the facility owner must regularly keep the transmission system operator informed if preliminary facility and model data are no longer representative of the completed, commissioned generation facility.

If significant modifications are made to the properties of an existing generation facility, the facility owner must submit an updated[1] and documented simulation model of the modified facility.

Model delivery is deemed complete only when the transmission system operator has approved the simulation models and required documentation submitted by the facility owner.

2.1 Special conditions for the submission of models for asynchronous generation facilities (Type C)

For asynchronous generation facilities (Type C), consisting of the same type of individual installations (e.g. a specific wind turbine type or photovoltaic inverter), where no site-specific features are used for the generation facility's control, protection and regulation functions, including farm controller, the required model delivery may take the form of a validated simulation model for the individual facility and farm controller, where this is used. Other model-technical requirements for this generation facility type are detailed in section 3.2.

The accompanying documentation must include descriptions of how the respective simulation model for an individual facility can be used in connection with any subsequent aggregation to represent the characteristics of the generation facility in the point of connection, and any limitations on the use hereof.

The simulation model must be verified as specified in section 0.

For asynchronous generation facilities (Type C) where external components, e.g. STATCOMs or energy storage units etc., are used or where site-specific features for the generation facility's control, protection and regulation functions, including a farm controller, are used, the model delivery must include the overall generation facility, cf. section 0, and comply with all other model-technical requirements, cf. section 0.

[1] The necessary model update is only required to comprise replaced facility components or control, regulation or facility protection systems, as it is assumed that the transmission system operator is already in possession of a valid simulation model for the relevant generation facility. If the transmission system operator has not received such a model, a significant modification to a generation facility requires the submission of a complete and fully documented simulation model in compliance with present model requirement specifications.

2.2 General documentation requirements

To ensure correct model application, the required simulation models must be documented in user guides. These must include descriptions of the simulation models' structural configurations as well as descriptions of simulation model parameterization and valid boundary conditions in the form of operating points and any grid condition restrictions (short-circuit and R/X ratios) in the point of connection and fault location in connection with the simulation of external events in the public electricity supply grid. The user guide must also contain information about special model-technical conditions, e.g. the maximum step size for the equation solver used in connection with the implementation of dynamic and transient simulations etc.

The user guide must also include descriptions of the control, protection and regulation functions implemented in the simulation model to be used when evaluating the generation facility's characteristics in the point of connection, where the following conditions should be in focus:

- Single-line representation of the simulation model's electrical main components up until the point of connection.
- Description of the simulation model's electrical input and output signals (electrical terminals), including relevant conditions in relation to measuring points used, their measuring units and base values.
- A comprehensive parameter list, where all parameter values must be stated in the enclosed data sheets for main components, block diagrams and transfer functions, etc.
- Description of structure and activation levels of protective functions used.
- Description of set-up and initialisation of the simulation model as well as any limitations to the application hereof.
- Description of how the simulation model can be integrated into a large grid and system model of the public electricity supply grid as used by the transmission system operator.
- Unique version control of simulation model and related documentation.

Model-specific documentation requirements are described in the following sections.

3. Model-technical requirements

3.1 Synchronous generation facilities

3.1.1 Requirements for static simulation model (static conditions and short-circuit ratio)

The simulation model of the overall generation facility must represent this facility's static and quasi-static properties in the point of connection, applicable to the defined normal operation range [1] and in all relevant static grid conditions under which the generation facility must be operational.

In this context, quasi-static properties include the characteristics of the generation facility in connection with a short circuit in the point of connection or anywhere in the public electricity supply grid. In this context, a short circuit may take the form of:

- A phase-to-earth short circuit with any impedance in the fault point.
- Phase-to-phase-to-earth or phase-to-phase short circuit with any impedance in the fault point.
- A three-phase short circuit with any impedance in the fault point.

The static simulation model must:

- be supported by model descriptions that, as a minimum, include function descriptions of the main modules in the model.
- Include descriptions of the individual model components and related parameters.
- Include descriptions of the set-up of the simulation model as well as any limitations to the application hereof.
- Include the characteristics of the generation facility's static operating ranges for active and reactive power, so that the simulation model is not erroneously operated in an invalid operating point.
- Allow for the use of all required reactive power control functions:
    - Power factor control (cos ϕ control) with indication of reference point.
    - Q control (MVAr control) with indication of reference point.
    - Voltage control, including parameters for droop/compounding with indication of reference point.
- Allow simulation of RMS values in the individual phases during symmetrical incidents and faults in the public electricity supply grid.
- Allow simulation of RMS values in the individual phases during asymmetrical incidents and faults in the public electricity supply grid.
- As a minimum, cover the 47.5-51.5 Hz frequency range and the 0.0-1.4 p.u. voltage range.

If the generation facility comprises several parallel generator units, the simulation model must represent the generation facility's characteristics in the point of connection, as described above. Simulation model parameter settings must contain complete data sets for each individual facility.

The simulation model submitted must be implemented in the most recent version of the simulation tool DIgSILENT PowerFactory, using the built-in grid component models and standard programming features, which must be reflected in the applied model structure, etc., The model implementation used must not require the use of special settings of or deviations from the standard settings for the simulation tool's numerical equation solver or otherwise prevent integration between the simulation model submitted by the facility owner and the more extensive grid and system model used by the transmission system operator.

The scope and level of detail of data for grid components and other equipment that form part of the facility infrastructure must enable the construction of a complete and fully operational simulation model as required in section 0.

If the static simulation model is identical to the dynamic simulation model described in section 3.1.2, the requirement for a separate static simulation model no longer applies.

The simulation model must be verified as specified in section 0.

3.1.1.1 Accuracy requirements

In general, the simulation model must show no properties that cannot be proven for the actual generation facility.

3.1.2 Requirements for dynamic simulation model (RMS model)

The dynamic simulation model of the overall generation facility (including ancillary consumption installations) must represent the facility's static and dynamic properties in the point of connection, applicable to the defined normal operation range [1] and in all relevant grid conditions under which the generation facility must be operational. The dynamic simulation model must be able to represent the static and dynamic properties of the generation facility in connection with set point changes for the facility's generation of reactive power, including change of control mode for this, as well as the following external incidents, or combinations of these external incidents in the public electricity supply grid:

- Generator-near faults seen from the point of connection in accordance with the required FRT characteristics [1], where a short circuit can take the form of:
  - A phase-to-earth short circuit with any impedance in the fault point.
  - Phase-to-phase-to-earth or phase-to-phase short circuit with any impedance in the fault point.
  - A three-phase short circuit with any impedance in the fault point.
- Disconnection, and possible subsequent automatic reconnection, of any faulty grid component in the public electricity supply grid, cf. the above fault sequence, and the resulting vector jump in the point of connection.
- Manual connection or disconnection (without prior fault) of any grid component in the public electricity supply grid and the resulting vector jump in the point of connection.
- Voltage disturbances and near-miss voltage collapses within the required minimum simulation period, cf. details below, and as a minimum within the transient start-up period for the generation facility's transition to a new static state.
- Frequency disturbances of a duration of less than the required minimum simulation period, cf. details below, and as a minimum within the transient sequence for the generation facility's transition to a new static state.
- Activation of imposed system protection (via an external signal) for quick regulation of the generation facility's active power generation in reference to a predefined final value and gradient.

The dynamic simulation model must:

- Be supported by model descriptions that, as a minimum, include Laplace domain transfer functions, sequence diagrams for applied *state-machines* and function descriptions of the arithmetical, logical and sequence-controlled modules used in the simulation model.
- Include descriptions of individual model components and their related parameters, including saturation, non-linearity, dead bands, time delays and constraint functions (non-wind-up/anti wind-up) as well as look-up table data and principles applied to interpolation, etc.
- Include descriptions and clear indications of the simulation model's input and output signals, which, as a minimum, must include the following:
    - Active power.
    - Reactive power.
    - Set points for:
        - Active power control.
        - Power factor control (cos ϕ control).
        - Q control (MVAr control).
        - Voltage control including parameters for droop/compounding used.
        - Frequency control (droop and deadband).
        - System protection measures (final value and gradient for active power control).
    - Signal for activation of system protection.
- Include descriptions of set-up and initialisation of the simulation model as well as any limitations to the application hereof.
- Include all required control functions [1].
- Include relevant protective functions that can be activated by external incidents and faults in the public electricity supply grid, implemented in the form of block diagrams with indication of transfer functions and sequence diagrams for the individual elements.
- Include the excitation system, voltage regulator, power system stabiliser (PSS) and any excitation equipment implemented in the form of standardised models [2].
- Include the excitation system's constraint functions (stator current constraint, volt/hertz constraint as well as overexcitation and underexcitation constraint) implemented in the form of block diagrams with indication of transfer functions and sequence diagrams for the individual elements.
- Include power and speed regulator, drive engine or turbine system implemented in the form of standardised models [3]. If it can be documented that the required model accuracy is not possible with a standardised model, an agreement can be made with the transmission system operator to use facility-specific models for these facility components.
- Include total mechanical oscillation mass models for relevant facility components (generators, drive engines, turbines, gears, switches and excitation systems), including documentation of inertia constants, natural frequencies as well as spring and damping constants for each drive train element.
- Allow simulation of RMS values in the individual phases during symmetrical incidents and faults in the public electricity supply grid.
- Allow simulation of RMS values in the individual phases during symmetrical incidents and faults in the *public electricity supply grid*.
- As a minimum, cover the 47.5-51.5 Hz frequency range and the 0.0-1.4 p.u. voltage range.
- Be able to demonstrate compliance with the requirements for the excitation system's dynamic responses, including requirements for the PSS on damping and phase compensation [1].

- Allow initialisation in a stable operating point based on a single load flow simulation without subsequent iterations. Show a time-derivative value (dx/dt) on initialisation for any of the simulation model state variables of less than 0.0001.
- Allow description of the generation facility's dynamic properties for at least 60 seconds after any of the above set point changes and external incidents in the public electricity supply grid.
- Be numerically stable through a simulation of minimum 60 seconds without application of a sequence of events or changes to boundary conditions, with simulated values for active power, reactive power, voltage and frequency remaining constant throughout the simulation.
- Be numerically stable through an instantaneous voltage vector jump of up to 20 degrees in the point of connection.
- Be capable of utilising numerical equation solvers with variable time step in the 1 to 10 ms range.
- Not contain encrypted or compiled parts (unacceptable), as the transmission system operator must be able to perform quality assurance on the results of the simulation model and maintain this without the restrictions of software updates, etc.

It is accepted that the simulation model may return a number of non-convergence error messages relating to applied external incident when running a simulation sequence. This will, however, generally be perceived as imperfections related to model implementation, and cause and mitigation proposals must appear from the relevant model documentation. If it can be documented that aspects of the simulation model's non-convergence will adversely impact the application of the transmission system operator's overall grid and system model, the simulation model in question will be rejected.

If the generation facility comprises several parallel generator units, the simulation model must represent the generation facility's characteristics in the point of connection, as described above. Simulation model parameter settings must contain complete data sets for each individual facility.

If parts of the simulation model's parameter set cannot be retrieved directly from the corresponding and required parameter extract from the generation facility's control, protection and regulation equipment, model documentation must include descriptions of the simulation model's parameter conversions and underlying data.

The simulation model submitted must be implemented in the most recent version of the DIgSILENT PowerFactory simulation tool, using built-in grid component models and standard programming features, which must be reflected in the model structure used, etc. The model implementation used must not require the use of special settings of or deviations from the standard settings for the simulation tool's numerical equation solver or otherwise prevent integration between the simulation model submitted by the facility owner and the more extensive grid and system model used by the transmission system operator.

To ensure unambiguous model implementation, the simulation model basic values for generator bay power and generator bay voltage must be indicated in accordance with the non-reciprocal per unit system [4], which must make up basic values in the model used for the generation facility's voltage regulator. The use of scaling factors must be stated explicitly for signals between the excitation system's other functions if different basic values are used for these partial models.

If the generation facility comprises main components, for example power and speed regulators, drive engine or turbine system, and modelling of these requires parameter adjustments as a function of the generation facility's current operating point to ensure the required model accuracy, model documentation, cf. the above, must include the necessary model parameter sets for each of the following operating points:

- 25% of rated active power generation.
- 50% of rated active power generation.
- 75% of rated active power generation.
- 100% of rated active power generation.

The scope and level of detail of data for grid components and other equipment that form part of the facility infrastructure must enable the construction of a complete and fully operational simulation model as required in section 2.

The simulation model must be verified as specified in section 0.

3.1.2.1 Accuracy requirements

The simulation model must represent the static and dynamic properties of the generation facility in the point of connection. The simulation model must thus respond sufficiently accurately in reflection of the physical facility's static response for an actual operating point and similarly for the dynamic response in connection with a set point change or an external incident in the public electricity supply grid.

The facility owner must ensure that simulation models are verified with the results of the compliance tests defined [1] as well as relevant test and verification standards and must submit the required documentation hereof.

At a minimum, the following simulation model control functions must be included in the model verification:

- Reactive power control:
    - Power factor control (cos ϕ control).
    - Q control (MVAr control).
- Voltage control (voltage reference point in the point of connection).
- Frequency control (required control functions).
- System protection interventions (final value and gradient for downward regulation of active power) - if required by the transmission system operator.

Simulation model accuracy as regards the required control functions must be verified using a calculation of the deviation between the model's simulated responses in relation to the corresponding measured value.

Appendix 1 lists the generation facility's electrical signals that are covered by the following accuracy requirements.

The following quantitative requirements must be met for each completed standard test to ensure an objective assessment of the simulation model accuracy. Please note that all criteria apply and that no criterion can override another.

Within the 0.1-5 Hz frequency range, the frequency response (Vt/Vref) accuracy for the excitation system and PSS must keep within the following tolerances:

(a) The deviation between the simulated amplitude and the corresponding measured amplitude must be less than 10% for any frequency within the defined frequency range.
(b) The deviation between the simulated phase angle and the corresponding measured phase angle must be less than 5 degrees for any frequency within the defined frequency range.

When it comes to the generation facility's dynamic characteristics (time domain phenomena) caused by e.g. set point changes for the facility's generation of reactive power, including change of the related control mode, as well as external incidents in the public electricity supply grid, the simulation model's corresponding response must meet the following accuracy requirements:

1. Deviations between simulated gradients (dx/dt) compared with corresponding measured gradients must keep within the following tolerances:
   (a) 10% amplitude deviation.
   (b) Time offset (positive or negative) of the gradient start time or end time must be less than 20 milliseconds.

2. The generation facility's simulated responses must not include momentary changes of amplitude in the form of positive or negative spikes of more than 10% of the corresponding measured value. If momentary amplitude changes occur that exceed the permissible level, and where this is solely attributable to numerical circumstances owing to the simulation tool used, this must be documented in the required model verification report.

3. Simulated quasi-static oscillations within the 0.1-5 Hz frequency range in the generation facility's active and reactive power generation and voltage must be damped, and the frequency deviation must be less than 10% of the corresponding measured value.

4. Taking into account any difference in simulated and measured voltage in the point of connection, the deviation between the generation facility's simulated active and reactive power generation must at all times during simulation be less than 10% of the corresponding measured value.

5. Taking into account any difference in simulated and measured voltage in the point of connection, the deviation between the generation facility's simulated static active and reactive power generation, in relation to the corresponding measured value, must be less than 2% of the rated generation capacity of the facility.

Accuracy requirements for the stipulated simulation model are regarded as complied with if all defined tolerances of permissible deviations have been met.

In general, the simulation model must show no properties that cannot be proven for the actual generation facility.

3.1.3 Requirements for transient simulation model (EMT model)

Not required.

3.1.4 Requirements for harmonic simulation model

Not required.

3.2 Asynchronous generation facilities

3.2.1 Requirements for static simulation model (static conditions and short-circuit ratio)

The simulation model of the overall generation facility must represent this facility's static and quasi-static properties in the point of connection, applicable to the defined normal operating range [1] and in all relevant static grid conditions under which the generation facility must be operational.

In this context, quasi-static properties include the characteristics of the generation facility in connection with a short circuit in the point of connection or anywhere in the public electricity supply grid. In this context, a short circuit may take the form of:

- A phase-to-earth short circuit with any impedance in the fault point.
- Phase-to-phase-to-earth or phase-to-phase short circuit with any impedance in the fault point.
- A three-phase short circuit with any impedance in the fault point.

The static simulation model must:

- Be supported by model descriptions that, as a minimum, comprise function descriptions of the main modules in the model.
- Include descriptions of the individual model components and related parameters.
- Include descriptions of the set-up of the simulation model as well as any limitations to the application hereof.
- Include the characteristics of the generation facility's static operating ranges for active and reactive power, so that the simulation model is not erroneously operated in an invalid operating point.
- Allow for the use of all required reactive power control functions:
    - Power factor control (cos ϕ control) with indication of the set point.
    - Q control (MVAr control) with indication of the set point.
    - Voltage control, including parameters for droop/compounding applied with indication of the set point.
- Allow simulation of RMS values in the individual phases during symmetrical incidents and faults in the public electricity supply grid.
- Allow simulation of RMS values in the individual phases during asymmetrical incidents and faults in the public electricity supply grid.
- As a minimum, cover the 47.5-51.5 Hz frequency range and the 0.0-1.4 p.u. voltage range.

If a simulation model is used to aggregate individual facilities for a common representation of the generation facility in the point of connection, the model must be able to represent the characteristics of the generation facility in the point of connection, cf. above. The accompanying documentation must include descriptions of the principles used for aggregation and any limitations on the use of this. Simulation model parameter settings must include complete data sets for the individual facilities and the aggregated facility.

The content and level of detail of the simulation models for the plant controller and individual generation facility must be such that these can be readily integrated into a large grid and system model as used by the transmission system operator and subsequently appear as a complete, fully functional simulation model as required in section 2.

The simulation model submitted must be implemented in the most recent version of the DIgSILENT PowerFactory simulation tool, using built-in grid component models and standard programming features, which must be reflected in the model structure used, etc. The model implementation used must not require the application of special settings of or deviations from the standard settings for the simulation tool's numerical equation solver or otherwise prevent integration between the simulation model submitted by the facility owner and the more extensive grid and system model used by the transmission system operator.

The scope and level of detail of data for grid components and other equipment that form part of the facility infrastructure must enable the construction of a complete and fully operational simulation model as required in section 2.

If the static simulation model is identical to the dynamic simulation model described in section 3.2.2, the requirement for a separate static simulation model no longer applies.

The simulation model must be verified as specified in section 4.

3.2.1.1 Accuracy requirements

In general, the simulation model must show no properties that cannot be proven for the actual generation facility.

3.2.2 Requirements for dynamic simulation model (RMS model)

The dynamic simulation model of the overall generation facility must represent the facility's static and dynamic properties in the point of connection, applicable to the defined normal operation range [1] and in all relevant grid conditions under which the generation facility must be operational. The dynamic simulation model must be able to represent the static and dynamic properties of the generation facility in connection with set point changes for the facility's generation of active and reactive power, including change of control mode for this, as well as the following external incidents, or combinations of these external incidents in the public electricity supply grid:

- Generator-near faults seen from the point of connection in accordance with the required FRT characteristics [1], where a short circuit can take the form of:
  - A phase-to-earth short circuit with any impedance in the fault point.
  - Phase-to-phase-to-earth or phase-to-phase short circuit with any impedance in the fault point.
  - A three-phase short circuit with any impedance in the fault point.

- Disconnection, and possible subsequent automatic reconnection, of any faulty grid component in the public electricity supply grid, cf. the above fault sequence, and the resulting vector jump in the point of connection.
- Manual connection or disconnection (without prior fault) of any grid component in the public electricity supply grid and the resulting vector jump in the point of connection.
- Voltage disturbances and near-miss voltage collapses within the required minimum simulation period, cf. details below, and as a minimum within the transient start-up period for the generation facility's transition to a new static state.
- Frequency disturbances of a duration of less than the required minimum simulation period, cf. details below, and as a minimum within the transient sequence for the generation facility's transition to a new static state.
- Activation of imposed system protection (via an external signal) for fast regulation of the generation facility's active power generation in reference to a predefined final value and gradient.

The dynamic simulation model must:

- Be supported by model descriptions that, as a minimum, include Laplace domain transfer functions, sequence diagrams for applied *state-machines* and function descriptions of the arithmetical, logical and sequence-controlled modules used in the simulation model.
- Include descriptions of and related parameter values for the individual model components, including saturation, non-linearity, dead band, time delays and constraint functions (non-wind-up/anti wind-up) as well as look-up table data and principles applied to interpolation, etc.
- Include descriptions and clear indications of the simulation model's input and output signals, which, as a minimum, must include the following:
    - Active power.
    - Reactive power.
    - Set points for:
        - Active power control.
        - Power factor control (cos ϕ control).
        - Q control (MVAr control).
        - Voltage control including parameters for droop/compounding used.
        - Frequency control (droop and deadband).
        - System protection measures (final value and gradient for active power control).
    - Signal for activation of system protection.
    - Control signals for any external grid components, e.g. STATCOMs or energy storage units, etc.
- Include descriptions of set-up and initialisation of the simulation model as well as any limitations to the application hereof.
- Include all required control functions [1].
- Include relevant protective functions that can be activated by external incidents and faults in the public electricity supply grid, implemented in the form of block diagrams with indication of transfer functions and sequence diagrams for the individual elements.

- Include all control functions[2] that can be activated during all relevant incidents and faults in the public electricity supply grid.
- Include the generation facility's power and speed regulator.
- Include a total mechanical oscillation mass model of the generation facility's drive train, including documentation of inertia constants, natural frequencies as well as spring and damping constants for each of the drive train mass elements, if this is relevant for the representation of the static and dynamic properties of the generation facility.
- Allow simulation of RMS values in the individual phases during symmetrical incidents and faults in the public electricity supply grid.
- Allow simulation of RMS values in the individual phases during symmetrical incidents and faults in the public electricity supply grid.
- As a minimum, cover the 47.5-51.5 Hz frequency range and the 0.0-1.4 p.u. voltage range.
- Allow initialisation in a stable operating point based on a single load flow simulation without subsequent iterations. Show a derived value (dx/dt) on initialisation for any of the simulation model state variables of less than 0.0001.
- Allow description of the generation facility's dynamic properties for at least 60 seconds after any of the above set point changes and external incidents in the public electricity supply grid.
- Be numerically stable through a simulation of minimum 60 seconds without application of a sequence of events or changes to boundary conditions with simulated values for active power, reactive power, voltage and frequency remaining constant throughout the simulation.
- Be capable of utilising numerical equation solvers with variable sample lengths in the 1 to 10 ms range.
- Be numerically stable through an instantaneous vector jump of up to 20 degrees in the point of connection.
- Not contain encrypted or compiled parts (unacceptable), as the transmission system operator must be able to quality assure the results of the simulation model and maintain this without the restrictions of software updates, etc.

It is accepted that the simulation model may return a limited number of non-convergence error messages relating to the applied external incident when running a simulation sequence. This will, however, generally be perceived as imperfections related to model implementation, and cause and mitigation proposals must appear from the relevant model documentation. If it can be documented that aspects of the simulation model's non-convergence will adversely impact the application of the transmission system operator's overall grid and system model, the simulation model in question will be rejected.

If a simulation model is used to aggregate individual facilities for a common representation of the generation facility in the point of connection, the model must be able to represent the characteristics of the generation facility in the point of connection, cf. above. The accompanying documentation must include descriptions of the principles used for aggregation and any limitations on the use of this. Simulation model parameter settings must include complete data sets for the individual facilities and the aggregated facility.

The content and level of detail of the simulation models for the farm controller and individual generation facility must be such that these can be readily integrated into a large grid and system model as

[2] Control functions in relation to the required generation facility fault ride through properties, including dynamic voltage support in connection with a voltage dip.

used by the transmission system operator and subsequently appear as a complete, fully functional simulation model as required in section 2.

If the generation facility incorporates external components, for example to comply with grid connection requirements or for the delivery of commercial ancillary services, the simulation model must include the necessary representation of these components as required in section 2.

The simulation model submitted must be implemented in the most recent version of the DIgSILENT PowerFactory simulation tool, using built-in grid component models and standard programming features, which must be reflected in the model structure used, etc. The model implementation used must not require the use of special settings of or deviations from the standard settings for the simulation tool's numerical equation solver or otherwise prevent integration between the simulation model submitted by the facility owner and the more extensive grid and system model used by the transmission system operator.

The scope and level of detail of data for grid components and other equipment that form part of the facility infrastructure must enable the construction of a complete and fully operational simulation model as required in section 2.

The simulation model must be verified as specified in section 4.

3.2.2.1 Accuracy requirements

The simulation model must represent the static and dynamic properties of the generation facility in the point of connection. The simulation model must thus respond sufficiently accurately in reflection of the physical facility's static response for an actual operating point and similarly for the dynamic response in connection with a set point change or an external incident in the public electricity supply grid.

The facility owner must ensure that simulation models are verified with the results of the compliance tests required [1] as well as relevant test and verification standards [5,6] and submit the required documentation hereof.

Since model verification includes the generation facility's static and dynamic properties in connection with external incidents in the public electricity supply grid and, correspondingly, in connection with set point changes for the facility's generation of active and reactive power, it is advisable to define accuracy requirements and handle the verification procedure for these issues separately, as described in the following.

3.2.2.1.1 Accuracy requirements in connection with external incidents in the public electricity supply grid

In this context, external incidents comprise momentary voltage changes measured in the generation facility's point of connection, e.g. in connection with the short circuit of a grid component or manual switching with a grid component in the public electricity supply grid. Test and verification of a generation facility's static and dynamic properties in connection with such external incidents is typically only done in connection with certification and type approval of the relevant generation facility. These standard tests are normally carried out for individual facilities where a well-defined voltage profile is applied to the generation facility, typically on the high-voltage side of the generator transformer used.

The primary purpose of these standard tests is verification and certification of the generation facility's compliance with the required FRT properties, including requirements for delivery of dynamic voltage support (added reactive current I_Q) during the fault sequence in accordance with the defined characteristics [1]. The results of these standard tests are used for the subsequent verification of the functional requirements set for and the accuracy of the simulation model.

The standard tests used for model verification must be performed and documented in accordance with definitions and descriptions defined in [6].

Model verification is based on an evaluation of the statistical accuracy of the simulation model, where accuracy is determined based on a calculation of the deviation between the model's simulated response and the corresponding measured value, defining the deviation as: $X_E(n) = X_{sim}(n) - X_{measured}(n)$. The calculated deviation is evaluated using the following statistical criteria defined in [6].

- MXE - Maximum deviation (maximum error).
- ME - Average deviation (mean error).
- MAE - Average mark (absolute) deviation (mean absolute error).

Appendix 1 lists the generation facility's electrical signals that are covered by the above accuracy requirements.

In order to ensure an objective assessment of the simulation model accuracy, the following quantitative requirements must be met for each of the standard tests performed as the deviations calculated for the model must be less than or equal to the permissible deviations specified in Table 2 for each of the [6] defined time periods (pre-fault, fault and post-fault).

The permissible deviations stated in Table 2 for the specified electrical signals are relative to generation facility base values of rated active power (for the evaluation of active power and reactive power values) as well as nominal current (for the evaluation of active and reactive current component values), cf. the definition in [6].

		Synchronous and negative-sequence components											
		Active power			Reactive power			Power (active component)			Power (reactive component)		
		MXE	ME	MAE	MXE	ME	MAE	MXE	ME	MAE	MXE	ME	MAE
Permissible deviation	Pre-fault	0.150	±0.100	0.120	0.150	±0.100	0.120	0.150	±0.100	0.120	0.150	±0.100	0.120
	Fault	0.170	±0.150	0.170	0.170	±0.150	0.170	0.500	±0.300	0.400	0.170	±0.150	0.170
	Post-fault	0.170	±0.150	0.170	0.170	±0.150	0.170	0.170	±0.150	0.170	0.170	±0.150	0.170

Table 2 Accuracy requirements - permissible deviation.

Accuracy requirements for the required simulation model are regarded as complied with if all defined tolerances of permissible deviations have been met.

In general, the simulation model must show no properties that cannot be proven for the actual generation facility.

3.2.2.1.2 Accuracy requirements in connection with changes to the generation facility’s operating point

In this context, the phrase changes to the generation facility’s operating point comprises manual changes to generation facility’s static operating point, for example in connection with a set point change to the facility’s generation of active power or corresponding changes to set points for other required control functions. Test and verification of a generation facility's static and dynamic properties in connection with such set point changes are typically done in connection with required compliance tests [1].

The primary purpose of these standard tests is verification of the generation facility's compliance with required static and dynamic properties in the point of connection, including compliance with the requirements defined in relation to, for example, response time and control gradients, activation levels for control and constraint functions as well as verification of the generation facility's operating range, etc.

The results of these standard tests are used for the subsequent verification of the functional requirements set for and the accuracy of the simulation model.

The standard tests used for model verification must be performed and documented in accordance with definitions and descriptions defined in [6].

At a minimum, the following simulation model control functions must be included in the model verification:

- Active power control.
- Reactive power control:
    - Power factor control (cos ϕ control).
    - Q control (MVAr control).
- Voltage control (voltage reference point in the point of connection).
- Frequency control (required control functions).
- System protection interventions (final value and gradient for downward regulation of active power) - if required.

The accuracy of the simulation model with respect to the required control functions must be verified using a calculation of the deviation of the model's simulated responses in relation to the corresponding measured value.

Appendix 1 lists the generation facility electrical signals that are covered by the above accuracy requirements.

In order to ensure an objective assessment of the simulation model accuracy, the following quantitative requirements, applicable to the generation facility's step response, cf. the definition in [6], must be met for each of the standard tests performed as the deviations calculated for the model must be less than or equal to the permissible deviations specified in Table 3 Accuracy requirements - permissible deviation.

	Rise time	Reaction time	Settling time	Overshoot	Steady state
	$X_E = X_{sim} - X_{measured}$	$X_E = X_{sim} - X_{measured}$	$X_E = X_{sim} - X_{measured}$	$X_E = X_{sim} - X_{measured}$	$X_E = X_{sim} - X_{measured}$
Permissible deviation	< 50 ms	< 50 ms	< 100 ms	< 15%	< 2% of P_{rated}

Table 3 Accuracy requirements - permissible deviation.

Accuracy requirements for the required simulation model are regarded as complied with if all defined tolerances of permissible deviations have been met.

In general, the simulation model must show no properties that cannot be proven for the actual generation facility.

3.2.3 Requirements for transient simulation model (EMT model)

The facility owner must submit a transient simulation model of the generation facility to the transmission system operator, complying with the following specifications:

- The EMT model must be built and implemented in PSCAD/EMTDC in the software version specified by the transmission system operator.
- If the generation facility consists of several identical generation units, the EMT model must represent each generation unit as well as an optional number of units for model aggregation.
- The EMT model may comprise precompiled and encrypted parts. The EMT model must be DLL-based and usable with Intel Fortran from version 12 up to and including the latest release on the date of the signing of the contract between the facility owner and the generation facility manufacturer. Dependence on PSCAD versioning updates is accepted, subject to the EMT model using standard components available to the user.
- It must be possible for the user to set the simulation time for the start of the EMT model's injection of apparent power.
- It must be possible for the user to set the simulation time for activation of the generation facility’s protection systems in the EMT model.
- The EMT model must be validated for simulations at different simulation time steps. The model must present approximately the same results at transient simulations at any time step in the valid range. The highest possible time step must be stated in the user guide.
- The EMT model must be able to be implemented functionally several times in the same PSCAD simulation file without requiring significant changes to be made. Therefore, it must be possible to use the EMT model as several "definitions" or "instances". If the model contains an alternative to the use of several "definitions" or "instances", this must be described in the user guide.
- The EMT model must support the use of PSCAD/EMTDC’s "snapshot" function. It is mandatory for the model to give the same response with and without the use of the snapshot function.
- It must be possible to initialise the model in maximum 3 seconds of simulation time.
- The EMT model must represent all components, control systems and protection systems relevant for EMT analyses.
- All relevant function settings in the generation facility’s control system that are relevant for EMT analyses and that can be changed either locally or remotely must appear as available parameters in the simulation model. The scope of the delivery must be approved by the transmission system operator.
- All electrical, mechanical, control and protection signals relevant to EMT analyses of the public electricity supply grid must be available in the EMT model. The scope of the delivery must be approved by the transmission system operator.
- Grid components and other equipment that form part of the facility infrastructure must be implemented in the EMT model to an extent and at a level of detail valid for EMT studies. This includes cables, transformers, filters, etc. The scope of delivery must be approved by the transmission system operator.

- For generation facilities with a mechanical drive train, the EMT model must include a mechanical oscillation mass model of the generation facility's drive train, including documentation of inertia constants, natural frequencies as well as spring and damping constants, if this is relevant for the representation of the static and dynamic properties of the generation facility.
- For generation facilities with a grid-connected converter, this must be modelled at transistor level for a proper representation in transient studies.
- The EMT model must represent the generation facility's FRT properties [1].
- If the generation facility has special functions, for example a control regime for a particularly weak grid, these functions must be included in the EMT model. A relevant model-technical description of the special functions and their restrictions must be included in the EMT model's user guide.
- The model must be valid for static operating conditions.
- The EMT model must be usable for EMT simulations of balanced and unbalanced faults and interruptions of the generation facility's connection to the public electricity supply grid.

3.2.3.1 Model submission

On submission, the EMT model must include the following:

- PSCAD/EMTDC simulation model - version according to agreement with the transmission system operator.
- User guide with descriptions of model limitations.
- Verification report for the EMT model.
- A functional PSCAD simulation model must be supplied for the generation facility connected to a simple model representation of the public electricity supply grid, for example a Thévenin-equivalent model.
- User guide must describe the EMT model assumptions and application.
- A detailed description of model limitations must be submitted, with a description of all facility functions that are not included in the EMT model, but which could be assumed to be of significance to the transient electrical properties and performance of the generation facility.
- The EMT model verification report must include a comparison of the PSCAD/EMTDC model's static and dynamic responses with measurements made on the actual generation facility. This does not include static harmonic matters.

3.2.3.2 Accuracy requirements

The accuracy of the required transient simulation model will be determined in the same way as for the dynamic simulation model (RMS model), see section 3.2.1.1, using appropriate filtering for the calculation of the fundamental frequency component of measured and simulated values. The method used for filtering is agreed between the facility owner and the transmission system operator. Thus, the accuracy requirements for the transient simulation model and the applied evaluation method are identical to those for the required dynamic simulation model.

3.2.4 Requirements for harmonic simulation model

The simulation model of the overall generation facility must represent the facility's emissions of harmonics and passive harmonic response (harmonic impedance) in the point of connection, applicable to the defined normal operation range [1] and in all relevant static grid conditions under which the generation facility must be operational.

The single-unit model provided must be a Thévenin equivalent, representative of the generation facility's emission of integer harmonics, indicated as RMS voltages as well as the facility's passive responses in the 50-2500 Hz frequency range. The model must include all relevant positive, negative and zero-sequence impedances within the specified frequency range at a resolution of 1 Hz.

If the facility consists of several generation units, an aggregated simulation model representative of total emissions and total passive harmonic responses in the point of connection must be submitted in addition to the single-unit model. Requirements for frequency range and resolution are identical to those for the single-unit model.

If the generation facility's emissions or impedances are dependent on the facility's operating point, the model must be submitted for three power levels at nominal voltage and zero reactive power: P = 0.0 p.u., P = 0.5 p.u. and P = 1.0 p.u. In addition, a description of the reactive power's impact on harmonic emissions and impedances must be included. In addition, the facility owner must submit a model based on the highest emissions per harmonic. This applies to both the aggregated and single-unit models. The facility owner shall document any dependencies on the operating point and ensure correct implementation in the models.

The facility owner shall specify a method for summation of emissions from several generation units. This can be done either by specifying requirement for setting the angle of the Thévenin voltage for each harmonic frequency specifically for each generation unit, or by using a summation law such as the one specified in [7]. If a summation law is applied, α coefficients must be specified by the facility owner. Explanations must be given for the selected α coefficient values for all harmonics. In both cases, the facility owner shall substantiate that the method applied results in a correct representation of the generation facility's total harmonic emissions.

The scope and level of detail of data about grid components and other components of the facility infrastructure must enable the creation of a complete frequency-dependent simulation model in the 50 Hz-2500 Hz frequency range. This includes cables, transformers, filters etc. The scope of the delivery must be approved by the transmission system operator.

3.2.4.1 Accuracy requirements

The method used for the creation of a model for the individual generation facility must be specified and approved by the transmission system operator. If model parameters are set based on measurements, a measurement report must be enclosed as documentation. In addition, an account must be given of how model parameters are set using the results in the measurement report. If model parameters are set based on calculations or simulations, the method used must be specified and examples of result processing for the deduction of model parameters given.

4. Verification of simulation model

The facility owner must ensure that simulation models are verified [1]. The facility owner must handle all aspects of the model verification tests, including providing necessary measuring equipment, data loggers and personnel. The facility owner must also ensure completion and documentation of the required model verification, including documentation of compliance with defined accuracy requirements for the simulation model.

The actual compliance tests must be done as specified in [1], where the scope of the verification model has been determined together with the transmission system operator, based on a proposal from the facility owner.

The facility owner must document the measurements used for verification of the simulation model for the generation facility in a report containing descriptions of each data set, including measuring equipment used and subsequent data processing, as well as boundary conditions for completed compliance tests and cause(s) of any deviations as regards specified boundary conditions.
Measured results are compared with the corresponding simulated results and the accuracy of the simulation model is documented in a verification report. The model verification procedure is deemed complete only when the transmission system operator has approved the model verification report submitted by the facility owner.

Time-series measurements used for verification of the simulation model must be attached to the verification report in CSV format (comma-separated values).

4.1.1 Verification requirements for static simulation model (static conditions and short-circuit ratios)

Verification is not required; However, it must be documented that the static simulation model is representative of the generation facility's static and quasi-static properties, where special focus should be on the facility's sub-transient and transient short-circuit contribution in connection with any fault in the public electricity supply grid.

4.1.2 Verification requirements for dynamic simulation model (RMS model)

The facility owner must verify the simulation model for the overall generation facility, including all required control modes and verification of the generation facility's static and dynamic properties by applying the set point changes and external incidents in the public electricity supply grid described in sections 3.1.2 and 3.2.2.

Model verification is based on measuring results obtained in connection with the completion of type tests or required compliance tests when commissioning the generation facility or by a combination of these, so that the set functional requirements for, and the accuracy of the simulation model can be verified.

For synchronous generation facilities consisting of several individual installations, model verification must be completed for each individual installation.

For asynchronous generation facilities that consist of several individual installations, have key control, protection, and regulation functions or use any external components, thus making these facilities come over as aggregate generation facilities in the point of connection, model verification must be completed at an aggregate level and thereby represent all generation facility properties in the point of connection. Requirements for this type of generation facility, cf. section 2, comprise specific simulation models for each type of individual installation (e.g. one model for each turbine type used) and for each type of external component (e.g. one model for each energy storage units used etc.), and so, modelling of these individual installations and external components must be verified separately.

4.1.2.1 Special conditions for the verification of models for asynchronous generation facilities (Type C)

There are no general requirements for model verification at an aggregate level in the point of connection for asynchronous generation facilities (Type C). Model verification for this type of generation facility can be achieved with (certified) type tests of individual installations or implementation of required compliance tests when commissioning the generation facility.

For asynchronous generation facilities (Type C) where external components, e.g. STATCOMs or energy storage units, are used or where site-specific features for the generation facility's control, protection and regulation functions, including a farm controller, are used, model verification must be completed at an aggregate level, thus representing the generation facility's overall properties in the point of connection, cf. section 4.1.2.

4.1.2.2 Required signals for verification of synchronous generation facilities

Subsequent model verification requires that the following measuring signals, as a minimum, are recorded for the compliance tests completed when commissioning the generation facility:

- Active power – measured in the point of connection.
- Reactive power – measured in the point of connection.
- Phase voltages – measured in the point of connection.
- Phase currents – measured in the point of connection.
- Grid frequency – measured in the point of connection.
- Active power – measured at the generator terminals.
- Reactive power – measured at the generator terminals.
- Phase voltages – measured at the generator terminals.
- Phase currents – measured at the generator terminals.
- Bay current – measured at the generator terminals (or for the excitation system, if used).
- Bay voltage – measured at the generator terminals (or for the excitation system, if used).
- AVR output signals from the power system stabiliser (PSS) (if a separate signal is available).
- AVR signals (alarms) for activating limit functions.
- Generator RPM.
- Frequency response for the excitation system and power system stabiliser (PSS) (Vt/Vref).
- Set points for:
    - Active power control.
    - Power factor control (cos ϕ control).
    - Q control (MVAr control).
    - Voltage control.
    - Frequency or speed control.
- Signal for activation of system protection.

4.1.2.3 Required signals for verification of asynchronous generation facilities

Subsequent model verification requires that the following measuring signals, as a minimum, are recorded for the type and compliance tests completed when commissioning the generation facility:

- Active power – measured in the point of connection.
- Reactive power – measured in the point of connection.
- Phase voltages – measured in the point of connection.
- Phase currents – measured in the point of connection.
- Grid frequency – measured in the point of connection.
- Active power – measured on the primary side of the generator transformer.
- Reactive power – measured on the primary side of the generator transformer.
- Phase voltages – measured on the primary side of the generator transformer.
- Phase currents (resulting) – measured on the primary side of the generator transformer.
- Phase currents (active component) – measured on the primary side of the generator transformer.
- Phase currents (reactive component) – measured on the primary side of the generator transformer.
- Control signals (alarms) for activation of *fault ride-through* functions.
- Generator RPM – where relevant.
- Set points for:
  - Active power control.
  - Power factor control (cos ϕ control).
  - Q control (MVAr control).
  - Voltage control.
  - Frequency or speed control.
- Signal for activation of system protection.

4.1.3 Verification requirements for transient simulation model (EMT model)

Identical to verification requirements for RMS model, cf. section 4.1.2.

4.1.4 Verification requirements for harmonic simulation model

No model verification requirement.

5. References

1. Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators.
2. IEEE Standard 421.5: Recommended Practice for Excitation System Models for Power System Stability Studies.
3. IEEE Dynamic Models for Turbine-Governors in Power System Studies PES-TR1.
4. P. Kundur, Power System Stability and Control, McGraw-Hill, 1994.
5. IEC 61400-21: Wind Turbines – Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines.
6. IEC 61400-27-2: Wind Turbines – Part 27-2: Electrical simulation models – Model validation.
7. IEC 61000-3-6: Electromagnetic compatibility (EMC) - Part 3-6: Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems.

Appendix 1

Synchronous generation facilities

Signals included in the model verification requirement:

- Active power – measured in the point of connection.
- Reactive power – measured in the point of connection.
- Phase voltages – measured in the point of connection.
- Phase currents – measured in the point of connection.
- Bay current – measured at the generator terminals (or for the excitation system, if used).
- Bay voltage – measured at the generator terminals (or for the excitation system, if used).
- Generator RPM.
- Frequency response for the control and regulation system models.

Asynchronous generation facilities

Signals included in the model verification requirement:

- Active power – measured in the point of connection (or on the primary side of the generator transformer for type tests).
- Reactive power – measured in the point of connection (or on the primary side of the generator transformer for type tests).
- Phase currents (active component) – measured in the point of connection (or on the primary side of the generator transformer for type tests).
- Phase currents (reactive component) – measured in the point of connection (or on the primary side of the generator transformer for type tests).