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ANNEX B – REQUIREMENTS FOR SIMULATION MODELS FOR HVDC FACILITIES - REV. 0

This specification of requirements presents Energinet's simulation model requirements for the connection of HVDC facilities. The specification of requirements is included as background material in connection with the implementation of EU regulation 2016/1447 of 26 August 2016 establishing a network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules (hereinafter the regulation), and thus concerns requirements for HVDC facilities.

The memo describes the following:

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

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Please note: This is a translation. In case of inconsistencies, the Danish version applies.

Contents

1. Background

Due to the ongoing transition of the electricity system, with conventional HVDC facilities gradually being phased out and replaced by more flexible HVDC facilities, the transmission system operator requires greater insight into these 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 carry out grid and system analyses, e.g. when connecting new HVDC facilities to the grid. This requires up-to-date and accurate simulation models of grid-connected demand, generation and HVDC 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 states. The simulation models aim to enable analyses of power flow, balanced and unbalanced faults, low-voltage ride-through (LVRT) incidents, harmonic conditions, flicker, significant voltage changes, interaction with other electronic equipment and subsynchronous oscillations. All simulation models must be able to show the specified operating conditions.

2. General simulation model requirements

Under the regulation, the facility owner must submit simulation models to the transmission system operator, and these simulation models must properly reflect the HVDC facility's steady-state and quasi-steady state properties. The facility owner must also submit a dynamic simulation model (RMS model) and a transient simulation model (EMT model) to the transmission system operator for time domain analyses. The facility owner must also submit a harmonic simulation model for analysis of the harmonic state of the public electricity supply grid, including the HVDC facility's contribution to harmonic emissions in the point of connection (POC).

The minimum scope of delivery of simulation models for the individual HVDC plant is:

- Static simulation model
- RMS simulation model
- EMT simulation model
- Harmonic simulation model

The facility owner must ensure that models are forwarded on time under current procedures for grid connection of HVDC facilities and other provisions in the regulation, meaning that both preliminary and final models are submitted.

The facility owner must ensure that simulation models are verified with the results of the compliance tests defined as well as relevant factory tests and must submit the required documentation hereof.

If the HVDC 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 models.

From the HVDC 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 HVDC facility.

If modifications are made to the properties of an existing HVDC 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 General documentation requirements

In order to ensure correct model application, the required simulation models must be documented in user instructions with 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 (including short-circuit ratios) in the point of connection to the public electricity supply grid in connection with the simulation of external events in the public electricity supply grid. The user manual must also contain information about special model-technical conditions, e.g. the maximum sample length for the equation solver used in connection with the implementation of dynamic and transient simulations, etc.

The user manual must also include descriptions of the control, protection and regulation functions implemented in the simulation model to be used when evaluating the HVDC 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 issues in relation to measuring points used, their measuring units and base values used for these.
- 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.
- Descriptions of set-up and initialisation of the simulation model as well as any limitations to the application hereof. Including model accuracy, for example taking into account bandwidth; accuracy must be documented by comparing measured data to model outputs.
- Threshold values such as maximum step size for equation solver used, software version, compiler version, etc.
- Description of how the simulation model can be integrated into a comprehensive grid and system model 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.

[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 HVDC facility. If the transmission system operator has not received such a model, a significant modification to an HVDC facility requires the submission of a complete and fully documented simulation model in compliance with present model requirement specifications.

3. Model-technical requirements

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

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

In this context, quasi-static properties include the characteristics of the HVDC facility in connection with a short circuit in the point of connection or anywhere in the public electricity supply grid. A short circuit may here 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 meet the following requirements:

- Must be underpinned by model descriptions that, as a minimum, comprise function descriptions of the main model modules.
- Must include descriptions of the individual model components and related parameters.
- Must include descriptions of the set-up of the simulation model as well as any limitations to the application hereof.
- Must include the characteristics of the HVDC facility's static operating ranges for active and reactive power, so that the simulation model is not erroneously operated in an invalid operating point. This must be stated in the grid connection point in the public electricity supply grid.
- Must allow for the use of all required reactive power control functions:
  - Power factor control (cos ϕ control) with indication of set point.
  - Q control (MVAr control) with indication of set point.
  - Voltage control, including parameters for droop/compounding applied with indication of set point.
- Must allow simulation of root-mean-square values in the individual phases during symmetrical incidents and faults in the public electricity supply grid.
- Must allow simulation of root-mean-square values in the individual phases during asymmetrical incidents and faults in the public electricity supply grid.
- As a minimum, must cover the 47.5-51.5 Hz frequency range and the 0.0-1.4 p.u. voltage range.
- If the HVDC facility has special functions, for example a control regime for a particularly weak grid, these functions must be included in the static model.

The content and level of detail of the simulation model for the HVDC facility must be such that the model can be readily integrated into a large grid and system model of the public electricity supply grid, 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 must be submitted 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 model structure used, etc. The model implementation used must not require the use of special settings for 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 a large-scale grid and system model as 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, the requirement for a separate static simulation model no longer applies.

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

3.1.1 Accuracy requirements

The simulation model must not show any properties that cannot be proven for the actual HVDC facility.

3.2 Requirements for dynamic simulation model (RMS model)

The dynamic simulation model of the overall HVDC facility must represent this facility's static and dynamic properties in the point of connection, applicable to the normal operating range defined in the regulation and in all relevant grid conditions under which the HVDC facility must be operational. The model must include all main electrical components, control and regulation functions.

The model must be built as described below (up to and including section 3.2.3), unless other arrangements can be made in the connection agreement.

The model must take into account the following external incidents – or combinations of these external incidents – in the public electricity supply grid:

- Facility-related faults, seen from the point of connection, in accordance with the FRT characteristic required by the regulation, where a short circuit will take the form of 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 HVDC facility's transition to a new static state.
- Frequency disturbances of a duration within the required minimum simulation period, cf. details below, and as a minimum within the transient start-up period for the HVDC facility's transition to a new static state.
- Activation of potentially imposed system protection (via an external signal) for fast regulation of the HVDC facility's active power exchange in reference to a predefined final value and gradient.

The dynamic simulation model must meet the following requirements:

- Must be underpinned 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.
- Must include descriptions of and related parameters for the individual model components, including saturation, non-linearity, dead band, time delays and constraint functions as well as look-up table data and principles applied to interpolation, etc.
- Must 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
    - Frequency control
    - Runback
    - Set points for the regulation of:
        - Active power
        - Power factor (cos ϕ control)
        - Reactive power
        - Voltage, including parameters for droop/compounding used
        - Frequency (droop and deadband)
        - System protection measures (final value and gradient for active power control)
    - Emergency Power Control (EPC-P)
    - Emergency Reactive Power Control (EPC-Q)
    - Power Oscillation Damping (POD)
    - Reactive power oscillation damping
    - Black start of the public electricity supply grid
    - Signal for activation of system protection
    - Control signals for any external grid components, e.g. STATCOMs or energy storage units, etc.
- Must include descriptions of set-up and initialisation of the simulation model as well as any limitations to the application hereof.
- Must include all control functions required in the regulation.
- Must include 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.
- Must include all control functions [2] that can be activated during all relevant incidents and faults in the public electricity supply grid.
- If the HVDC facility has special functions, for example a control regime for a particularly weak grid, these functions must be included in the RMS model. A relevant model-technical description of the special functions and their restrictions must be included in the RMS model's user instructions.
- Must include the characteristics of the generation facility's static and dynamic operating ranges for active and reactive power, so that the simulation model is not erroneously initialised and operated in an invalid operating point. This must be stated in the grid connection point for the public electricity supply grid.

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

- As a minimum, must cover the 47.5-51.5 Hz frequency range and the 0.0-1.4 p.u. voltage range.
- Must allow initialisation in a stable operating point on the basis of a single load flow simulation without subsequent iterations. Must show a derived value (dx/dt) on initialisation for any of the simulation model state variables of less than 0.0001.
- Must allow description of the HVDC 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.
- Must 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.
- Must be capable of utilising numerical equation solvers with variable sample lengths (in the 2 to 5 ms range).
- Must be numerically stable through an instantaneous vector jump of up to 20 degrees in the point of connection.
- Must not contain encrypted or compiled parts, 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.

The fact that the simulation model may return a number of non-convergence error messages relating to applied external incident when running a simulation sequence is accepted. 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 the simulation model's non-convergence will adversely impact the application of the transmission system operator's comprehensive grid and system model, the simulation model in question will be rejected. Similarly, the facility owner is responsible for providing support in relation to updates if it is determined that the simulation model does not correspond to facts when the facility is completed.

The content and level of detail of the simulation model for the HVDC facility must be such that the model can be readily integrated into a large grid and system model of the public electricity supply grid, as used by the transmission system operator, and subsequently appear as a complete, fully functional simulation model as required in section 2.

If the HVDC 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 must be submitted implemented in the most recent version of the simulation tool DIgSILENT PowerFactory, using the built-in grid component models and standard programming features (macros), which must be reflected in the model structure used, etc. The model implementation used must not require the use of special settings for 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 a large-scale grid and system model as 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.

3.2.1 Accuracy requirements

The simulation model must represent the static and dynamic properties of the HVDC 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 static 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 in the EU regulation and must submit the required documentation hereof.

Since model verification includes the HVDC 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 exchange 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 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 HVDC 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.

One purpose of the defined compliance tests is verification and certification of the HVDC 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 characteristics defined in the EU regulation. The results of these factory tests are used for the subsequent verification of the functional requirements defined for - and the accuracy of - the required simulation model.

The simulation model must not show any properties that cannot be proven for the actual HVDC facility.

3.2.3 Accuracy requirements in connection with changes to the HVDC facility's operating point

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

The primary purpose of these standard tests is verification of the HVDC 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 HVDC facility's operating range, etc.

Factory test results are used for the subsequent verification of the functional requirements defined for - and the accuracy of - the required simulation model.

At a minimum, the following simulation model control functions must be included in 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 for the HVDC facility.

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.

Section 4.2.1 lists the HVDC facility electrical signals that are subject to the above accuracy requirements.

In general, the simulation model must not show any properties that cannot be proven for the actual HVDC facility.

3.3 Requirements for transient simulation model (EMT model)

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

- The EMT model must be built and implemented to PSCAD/EMTDC in the software version specified by the transmission system operator.
- The EMT model must include precompiled and encrypted parts; However, such parts must not result in limitations when the transmission system operator implements the model in the grid model of the public electricity supply grid, which includes, for example, models of the existing HVDC facilities. 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 HVDC unit manufacturer. The model must not result in any limitations in connection with PSCAD version updates. Standard components available to the transmission system operator must be used, allowing the transmission system operator to take the necessary steps to be able to use the model in future versions of PSCAD.
- 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 HVDC 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 in simulations at any time step in the valid range. The highest possible time step must be stated in the user instructions.

- 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.
- The plant owner must take the necessary steps to ensure the lowest possible simulation time for initialisation of the EMT model. As part of the documentation, it must be quantified in which circumstances the EMT model can be seen as being fully initialised.
- The EMT model must represent all components, control systems and protection systems relevant for EMT analyses.
- All relevant function settings in the HVDC 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, 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.
- The EMT model must be modelled at transistor level.
- The EMT model must represent the FRT properties of the HVDC facility as required in the EU regulation.
- If the HVDC 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 instructions.
- The EMT 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 HVDC facility's connection to the public electricity supply grid.
- It must be possible to use the EMT model for dead start studies and island operation.

3.3.1 Model submission

On submission, the EMT model must include the following:

- PSCAD/EMTDC simulation model (version stated by the transmission system operator).
- User instructions with descriptions of model limitations.
- Verification report for the EMT model.
- A functional PSCAD simulation model must be supplied for the HVDC facility and must be connected to a simple model representation of the public electricity supply grid, for example represented by a Thévenin-equivalent model.
- User instructions must describe the EMT model assumptions and application instructions.
- A detailed description of model limitations must be submitted, with a description of all HVDC facility functions that are not included in the EMT model, and which could be assumed to be of significance to the transient electrical properties of the HVDC facility.
- The EMT model verification report must include a comparison of the PSCAD/EMTDC model's static and dynamic responses with measurements made in the physical HVDC facility. For this purpose, a real-time simulator that includes the physical control system can be used. Static harmonic matters are not subject to this requirement.

3.3.2 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 3.1.1, 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.

3.4 Requirements for harmonic simulation model

The simulation model of the overall HVDC facility must represent the facility's emission of harmonics and static harmonic response (frequency-dependent impedance) in the point of connection, applicable to the normal operating range defined in the EU regulation and in all relevant static grid conditions under which the HVDC facility must be operational.

The harmonic simulation model provided must be a Thévenin equivalent, representative of the HVDC facility's emission of harmonics, indicated as RMS voltages, and of the facility's passive responses in the 50-2500 Hz frequency range. The model must include all relevant positive, negative sequence and zero-sequence impedance within the specified frequency range with a resolution of 1 Hz. Active emission of integers and interharmonics must be included in the model.

If the HVDC facility's emission and/or impedance is dependent on the facility's operating point, the model must be supplied at three operating points 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 effect's impact on harmonic emissions and impedances must be included. Also, the facility owner must supply a model created with the highest emission per harmonic. The facility owner must document any dependencies on the operating point and ensure correct implementation in the models.

3.4.1 Accuracy requirements

The method used to create the model for the HVDC facility must be specified and approved by the transmission system operator. If model parameters are set based on measurements, the facility owner must enclose a measurement report 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 in agreement with the EU regulation. The facility owner must handle all aspects of the model verification tests, including providing necessary measuring equipment, data loggers and personnel. Furthermore, the facility owner is responsible for the completion and documentation of the required model verification.

The actual factory tests must be done as specified in the EU regulation, which states that the scope of model verification is to be determined jointly 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 HVDC 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.

4.1 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 HVDC facility’s static and quasi-static properties, with special focus on the facility's subtransient and transient short-circuit contribution in connection with any voltage dip in the public electricity supply grid.

4.2 Verification requirements for dynamic simulation model (RMS model)

The facility owner must verify the simulation model for the overall HVDC facility, including all required control modes and verification of the HVDC facility’s static and dynamic properties by applying the set point changes and external incidents in the public electricity supply grid described in section 3.2.

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

4.2.1 Extent of signals required for verification of HVDC facility

Subsequent model verification requires that the following measuring signals, as a minimum, are recorded for the factory and compliance tests performed when commissioning the HVDC 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
- Modulation index
- Control signals (indicators) for activation of fault ride-through functions

- Set points for:
  - Active power control
  - Power factor control (cos ϕ control)
  - Q control (MVAr control)
  - Voltage control
  - Frequency control
- Signal for activation of system protection

4.3 Verification requirements for transient simulation model (EMT model)

Identical to verification requirements for RMS model, cf. section 4.2.

4.4 Verification requirements for harmonic simulation model

No model verification requirement.