Offshore Grid Connection Requirements

Annex: Simulation Models and Studies

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List of Abbreviations

DLL	Dynamic Link Library
DSL	DIgSILENT Simulation Language
DSP	Digital Signal Processor
EMT	Electro-magnetic transient
FNN	Forum Netztechnik/Netzbetrieb - Forum Network Technology/Network Operation
FPGA	Field Programmable Gate Array
FPT/ DPT	Functional / Dynamic performance test
FRT	Fault Ride Through
HIL	Hardware in the Loop
HVDC	High Voltage Direct Current
HVRT/ LVRT	High/ Low Voltage Ride Through
IGBT	Insulated-Gate Bipolar Transistor
ONAR	Offshore Netzanschlussregel – Offshore Grid Connection Requirements
OWF	Offshore Windfarm
PCC	Point of Common Coupling
PLL	Phase Lock Loop
PPM	Power Park Modules
$Q_{AC,max/min}$	Maximum/Minimum Reactive Power infeed at maximum active power infeed
RMS	Root Mean Square
SIL	Software in the Loop
TSO	Transmission System Operator
VDE	Verband der Elektrotechnik Elektronik Informationstechnik - Association of Electrical, Electronic & Information Technologies
WTG	Wind turbine generators

1 INTRODUCTION

This attachment describes the minimum requirement on the simulation models of the Offshore Wind Farm (OWF) and the belonging Wind Turbine Generators (WTG), which shall be submitted to the Transmission System Operator (TSO) in the grid compliance procedure. The primary goals of the simulation model requirement are the independency of the model from simulation tools and tool versions so that the TSO can perform studies in the future without any limitation due to tool- and version-dependency.

The requirements in this attachment of the ONAR are complementary to the existing requirements for simulation models and studies in VDE Application Rule VDE-AR-N 4131, Annex B.6.

2 MODEL REQUIREMENTS

2.1 GENERAL REQUIREMENTS

All calculation and simulation models shall be created in line with requirements before the OWF is installed and must be submitted to the TSO.

The respective models shall be able to suitably represent the actual behaviour of the OWF and its belonging WTGs for all relevant operating situations (normal operation, behaviour in the event of short circuits, etc.).

If parameters are changed during the trial run, the OWF operator shall update the models and make them available to the TSO. It shall be ensured that the TSO can receive updated models during the entire service life of the OWF. The OWF operator shall provide the TSO with support for at least 24 months after the submission of each updated model. This support shall encompass at least 40 hours per model.

The OWF operator shall supply the models together with the study report in which they are used. The OWF operator shall provide the final and validated versions of all models described in this document once the FPTs and DPTs are complete.

If changes are made after this point, the OWF operator shall supply the updated and validated models within one month.

If phenomena are observed during the trial run or operation phase that cannot be reproduced by the supplied models, the OWF operator shall check and optimise these models to enable the TSO to simulate these phenomena.

All reports shall specify the author and the software used, including the software version as well as compiler and visual studio version if used. If a diagram shows several curves, a suitable key or description must be provided to indicate which curve is which.

Model documentation must comprise the operating instructions and validation documentation.

2.2 STEADY-STATE AND DYNAMIC MODELS

The following models of the entire OWF including the park controller and its belonging WTGs and a separated individual WTG model shall be provided:

1. Model for large signal and small signal stability calculations (**RMS simulation with balanced and unbalanced network modelling** as well as **modal analysis**) including transfer functions of the current control loops.
2. Modelling for **steady-state calculations** (load flow calculations, short-circuit current calculations), as implementation **within the RMS model**
3. Model for simulations in the instantaneous value range (**EMT simulations** with three-phase network modeling) including all specific control and dynamic characteristics as well as relevant protection functions and time delay.
4. Model for **frequency domain calculations** (harmonic spectrum and frequency dependent impedance). The models shall be represented as a Thévenin equivalent for this purpose. The frequency-dependent impedance Z(f) and voltage U(f) shall be given in tabular form for steady-state operation for each harmonic from the 1st to the 50th harmonic with real and imaginary parts. Different operating points must be considered.

The models shall be in general available for viewing (no black box models) and encompass all other relevant primary-technology equipment (such as transformers including saturation, reactors, switches, and filters).

In general, the parameters of all controllers shall be adjustable. The setting ranges of these parameters shall be included in the model, and any parameterisation outside these ranges shall be acknowledged with corresponding warning or error messages.

All operating points and operating modes specified in (VDE-AR-N 4130 and VDE-AR-N 4131) and this ONAR shall be able to set in the models.

A detailed description including instructions for using the model shall be provided for each model.

The TSO specifies which versions of the simulation software as well as compiler and visual studio is required for the project at hand.

2.2.1 MODEL ACCURACY

The delivered models shall be validated by means of measurements. If no such measurements are available, the RMS models shall be validated using the more detailed EMT models from the OWF operator.

The models shall be validated and, if necessary, updated using the test results of the FATs and commissioning tests.

The control system behaviour requirements specified in this ONAR regarding the transient response of all relevant control functions shall be demonstrated in the dynamic performance test (DPT).

Table 1: Accuracy requirements applicable to RMS/EMT models

Scale of time response	Maximum deviation between simulation and measurement
Step response time deviation	10 ms
Steady state deviation	3%
Maximum transient overshoot deviation	5%[1]
Settling time deviation	10 ms

2.2.2 ROOT MEAN SQUARE (RMS) MODELS

The OWF operator shall use **DIgSILENT PowerFactory** to develop a detailed RMS model (effective value simulation model) for OWF and make this model available to the TSO. The model shall be able to run on **64-bit systems**.

The model shall be valid in the millisecond range. The **simulation step size** shall be adjustable at least in the range of **1 to 10 ms**. The model shall run with automatic step size adaptation.

The model shall enable the performance of stability tests. The DIgSILENT PowerFactory initialisation method shall ensure the correct and automated initialisation of the model for all operating points in all operating modes. Deviations from the initialised values at the start of the simulation shall be avoided, along with error and warning messages in the message window of the simulation software. Information messages shall be kept to a minimum and properly documented. The model shall start with a flat run in the dynamic calculation not triggering any transients in the AC network model.

The model shall properly depict the control systems that influence the behaviour of the system in the relevant time range for RMS simulations. The model shall take into account the effects of measurement systems (e.g., time delays). The simplification of the converter synchronisation mechanism (PLL) shall be discussed and documented.

The model shall include all data relevant to steady-state load flow and short-circuit calculations alongside the RMS simulation functionality. These include the reactive power capacity, short-circuit power or current contribution, the X/R ratio in the positive-phase sequence system, and zero-phase sequence system impedances.

The model shall include tap changer control for load flow as well as for dynamic simulations, if applicable.

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[1] If, for example, the measured overshoot of the real system is 8%, then the model may have an overshoot between 3% and 13%.

The model shall contain the protective functions active in the specified frequency range, including delays caused, for example, by signal processing. The following shall be included as a minimum:

- Undervoltage and overvoltage protection
- Frequency protection
- Overcurrent protection

The model shall be implemented directly in DIgSILENT PowerFactory (by means of DSL[2] code or the graphic interconnection of DSL macros) without using external, pre-compiled components (e.g., DLL files). If it is necessary to use encryption or pre-compiled components, the OWF operator shall supply two models:

1. An **open, unencrypted** RMS model, completely implemented in DIgSILENT PowerFactory (by means of DSL code or the graphic interconnection of DSL macros), which may involve simplified modelling for selected parts of the control system to protect intellectual property, as the case may be. Model inaccuracies caused by such simplifications shall be described, documented, and evaluated during validation. However, general conformity with the simulation results from the model and the measured system behavior shall be achieved.
2. A **detailed RMS model** that depicts the control system and system behaviour as accurately as possible. This model may be implemented using external, pre-compiled components (e.g., DLL files) or encrypted DSL code.

Furthermore, the encrypted model components shall fulfil the following requirements:

- If parts of the model must be encrypted to protect intellectual property, only the control code may be encrypted.
- Block diagrams of these parts shall be provided (for easier integration into other grid models).
- Primary equipment shall not be encrypted.
- If applicable, the header of the encrypted parts shall be open.
- If all or part of the control system is encrypted, the TSO shall be able to access and adjust the following signals, settings, and parameters:
    - Dynamic current limitations
    - All necessary functions and control modes in accordance with this ONAR
    - Setpoints of all necessary functions and control modes in accordance with this ONAR
    - The parameters of all necessary functions and control modes in accordance with this ONAR
    - Mechanisms for activating/deactivating FRT (LVRT and HVRT)
    - External access in AC current controller signals

2.2.2.1 VALIDATION

The RMS model shall be verified by the validated EMT model or by the factory test results (real-time simulations with the actual control system implementation). The OWF operator shall

[2] DIgSILENT Simulation Language

propose suitable scenarios and fault cases for the validation including different operating points and control mode settings. The simulation results shall be confirmed by the measurements performed during the commissioning tests or grid compliance test, once commissioning is complete.

The OWF operator and the TSO shall agree on the scenarios to be used for validation purposes, taking into account the following aspects as a minimum:

- The dynamic behaviour for changes in the operating point
- The dynamic behaviour for all control modes, as well as functional tests of relevant control functions (e.g., AC voltage control, active and reactive power control, LFSM-O/U, FSM, EPC activation (if applicable)
- The dynamic behaviour in case of faults in the AC system
- The dynamic behaviour in the event of voltage jumps at PCCs
- The dynamic behavior in the event of frequency changes in the AC system
- The dynamic behavior for selected cases for grid forming control, if applicable
- The accuracy requirements for the validation shall be complied with Table 1.

2.2.3 EMT MODELS FOR INSTANTANEOUS VALUE SIMULATIONS

A model for instantaneous value simulations (EMT simulations) shall be provided. Additionally, the equivalent circuit diagram shall be specified containing all power components with the corresponding parameters, measuring points, and actuators. This model shall be provided in a well-established simulation program such as **PSCAD**. Transformation of the model between different programs shall be avoided during the project.

The model shall allow simulations on sources of influence, such as controller interactions with other nearby power electronic systems (HVDC systems, wind farms, other OWFs, etc.), dynamic performance.

The represented system shall be divided into three parts:

1. **Power components:** The power components comprise all electrical, magnetic, and mechanical components such as transformers, converters, etc.
2. **Control hardware:** The "control hardware" includes the hardware that is not part of the power components. It is typically used for system control and protection. This control hardware may include digital systems such as industrial PCs or electronic assemblies with microprocessors, digital signal processors, or FPGAs. This part also includes analog control systems such as hardwired protection systems.
3. **Control and protection software:** The "control software" includes the software that is executed on the control hardware that realizes functions of the control and protection system. For example, this includes the software for controlling the power converters or for generating pulse patterns for the IGBTs. This part also contains software for simulating special control functions that are implemented in the system without software (e.g., analog protection systems, which are emulated in the simulation with control software).

Model requirements:

- The model shall be valid in a frequency range **between 0 Hz and 9,000 Hz**.
- The model shall be independent from compiler versions.
- The model shall be independent from visual studio versions.
- The model shall be portable to other simulation tools, which may be conducted by the TSO or third parties.
- The model shall depict the real control, measurement, and protection system as well as the real interfaces of the real hardware. .
- Power components and primary-technology equipment shall not be encrypted.
- The model shall be able to calculate the converter's frequency dependent output impedance for different configurations and operating points.
- The setpoints, protection parameters and ramps shall be freely adjustable. The setting ranges of these parameters shall be included in the model and any parameterisation outside these ranges shall be acknowledged with corresponding warning or error messages.
- The model shall not contain compiled Fortran code
- The model shall initialise itself automatically for all operating points and operating modes and reach a stable status after a simulation time of 3 seconds at the latest.
- The model shall support the snapshot and multiple run functions.
- The model shall take into account all design limits.
- The model shall contain a pulse pattern generator that can be deactivated to reduce the simulation time. The simplified pulse pattern generation shall be implemented following the type 5 ("Average Value Models") from the CIGRÉ WG B4.57[3].
- The model shall contain predefined fault cases, which are necessary for the performance of the studies. The fault cases must be adjustable.
- The model shall contain the protective functions active in the specified frequency range, including delays caused, for example, by signal processing. If a protective function leads to a trip, the model needs to show which functions are triggered. The following shall be included as a minimum:
    - Undervoltage and overvoltage
    - Frequency
    - Overcurrent
    - di/dt
    - Harmonics
    - Current or voltage imbalances
- A dynamic library with defined interfaces (DLL file) of the encrypted control software shall be provided for each physical control system. **32-bit and 64-bit versions** shall be supplied.
    - If the control system consists of several processors (e.g., DSP or FPGA) that exchange values with each other, a DLL shall be created for each processor. If

[3] CIGRÉ, WG B4.57, Guide for the Development of Models for HVDC Converters in a HVDC Grid, 2014

a DLL is used several times, e.g., pulse pattern generation per arm, it shall be ensured that any multiple access to global variables is prevented.

  - The interfaces shall be based on the "ENTSO-E Standardized control interface for HVDC SIL/HIL conformity tests"[4]. Not required interfaces for an OWF shall be substituted with "spare". Moreover, the OWF operator and the TSO shall agree on further details of the DLL interfaces.

- If the system may consist of several independently controlled inverter blocks. Then, the DLLs shall be developed and submitted with a unique name for each inverter block. Using several DLLs in one control system that access each other is not permitted.

Simulation requirements:

- The timestep of the simulation tool shall be arbitrary. If this is not possible the simulation timestep shall be settable in the **range of 1 µs to 20 µs**. The OWF operator shall record the applicable time step sizes.
- Multiple instantiations of a plant in one network model shall be possible

Documentation requirements:

- If parts of the model must be encrypted for intellectual property-related reasons, **only the control code may be encrypted**.
- A **signal flow diagram** of these parts must be provided (for easier integration into other grid models).
- The equivalent circuit diagram and the parameters of the power components shall be specified. This circuit diagram shall contain all components relevant for system functionality. The corresponding specifications shall be provided in a list of possible components.
- The following information of the **control hardware** shall be provided:
  - **Inputs**: A table with all input variables shall be provided. Inputs may comprise the measuring points of the power unit or the outputs of connected control hardware.
  - **Outputs**: A table of the outputs shall be provided to enable correct assignment. These outputs may be inputs of connected control hardware or actuators of the power components.
  - Each control hardware shall execute exactly one control software. Therefore, the control software shall be mapped to the corresponding control hardware.

If all or part of the control is encrypted, the TSO shall be able to access and adjust the following signals, settings, and parameters:

[4] ENTSO-e. ENTSO-E Standardized control interface for HVDC SIL/HIL conformity tests. 2020.

- Grid (primary) voltage and current of the converter transformer
- Converter-side (secondary) voltage and current of the converter transformer
- Neutral point voltage and current of the converter transformer (if applicable)
- Reactive power on the primary side of the converter transformer
- Devices used to activate or deactivate protective mechanisms and provide information on which protective system has been triggered
- Signals used to trigger protective systems
- All reference signals relevant to control systems, e.g., voltage reference signals for pulse pattern generation
- Measured and filtered voltages and currents before they are used in the control system
- PLL deviation
- All necessary functions and control modes in accordance with this ONAR
- Setpoints and parameters of all necessary functions and control modes in accordance with this ONAR
- Mechanisms for activating/deactivating FRT (LVRT and HVRT)
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Moreover, all parameters of the control software that can be adjusted externally shall be listed in the documentation.

2.2.3.1 DLL INTERFACES

The DLL interfaces for the encrypted control software may be defined in a C-code header that is typically used for creating DLL files. Thus, C-code shall be used to create the DLL files. Moreover, it is mandatory to consider the defined interfaces while creating the DLL files. These requirements lead to the following structure:

1. External callable functions in the DLL-files
    - Initialisation: function_init
    - This function is called once during simulation start.
    - Calculation: function_run
    - This function is executed cyclically during the simulation run.
    - Termination: function_release
    - This function is called to end the simulation.
    - Reset: function_reset
    - This function is called to reset the control software to the initialization state.
2. Function interfaces
    - The structure „control_data_input“ provides the inputs for the control software.
    - The outputs are given by the control software using the structure „control_data_output“.

In addition, the following notes shall be considered for the DLL files and their interfaces:

1. The required DLL interfaces are mandatory.
    - The C header defines both, the functions, and their interface parameters, which must be considered because otherwise the control DLL may be executed with errors.
2. The input and outputs shall contain the direct values of the control software.
    - The C-header defines the inputs and outputs of the functions as vectors. These vectors contain the direct values of the control software like they are transferred

between the control hardware in the real system. Using memory addresses to transfer data is not permitted.
- Furthermore, the data types of the vector defined in the header shall be used. For example, a uint_8_t value may not be transferred without casting it to the data type of the vector defined in the header.

3. Different DLL files shall not share memory locations.
   - In many controllers, internal memory is necessary to persistently store values and reuse them in the next calculation cycle of the controller. For this purpose, memory locations may be reserved in the DLL and used in the calculations. However, these memory locations are only allocated to the single DLL and shall not be shared between multiple DLL files. Different DLL files shall only transfer data between each other by using the defined vectors of the interface.
4. It is not permitted to extend the control function in comparison to the real system. The control DLL shall represent the same control implementation like in the real system. It is not permitted to use additional functions, which for example use physical quantities that are not used by the control of the real system.

2.2.3.2 USER INTERFACE

The OWF operator shall implement a graphical user interface, e.g., with buttons, sliders, switches for setting different switching configurations, setpoints and control modes of the OWF that are possible during operation. The OWF operator shall integrate a graphical user interface for each converter with hybrid extension so that it is possible to change the following settings during simulation:

- Blocking of the converter: on/off
- Converter transformers: on/off
- Neutral earthing: open/closed (if available)
- Selection of control modes
- Setpoints of the various control modes
- Status of the active filter function
- Parameters for the active filter function
- Third harmonic activated/deactivated (if applicable)
- Status of all circuits

The OWF operator shall integrate a graphical user interface for the equivalents of the AC grid at the PCC so that the following settings can be changed during simulation:

- Selection of a detailed AC equivalent model or Thevenin equivalent
- Setpoint for *S*k‘‘ (short-circuit power), if a Thevenin equivalent is selected

2.2.3.3 VALIDATION

The EMT model shall be checked against the test results of the factory test (real-time simulations with the actual control system implementation).

The OWF operator shall propose suitable scenarios and fault cases for the validation including different operating points and control mode settings.

The simulation results shall be confirmed by the measurements performed during the commissioning tests, once commissioning is complete.

The OWF operator and the TSO must agree on the scenarios to be used for validation purposes, taking into account the following scenarios and aspects as a minimum:

- Fault in the WTG
- Fault in the Offshore AC system (balanced and unbalanced)
- Change in the operating point
- The dynamic behaviour for all control modes, as well as functional tests of relevant control functions (e.g., AC voltage control, active and reactive power control, LFSM-O/U, FSM, EPC activation (if applicable)
- The dynamic behaviour in case of faults in the AC system
- The dynamic behaviour in the event of voltage jumps at PCCs
- The dynamic behavior in the event of frequency changes in the AC system
- The dynamic behavior for selected cases for grid forming control, if applicable
- The accuracy requirements for the validation shall be complied with Table 1.

2.2.4 HARMONIC MODEL FOR HARMONIC PERFORMANCE AND STABILITY

The OWF operator shall develop a harmonic model for OWF and use this model in the harmonic study and for the interaction screening.

Such models shall be supplied in a machine-readable format (e.g., text files or Excel spreadsheets) and shall be valid for the frequency range from 0.1 Hz to 9,000 Hz as a minimum, with a maximum frequency step of 1 Hz. Measurements and calculation results shall be taken into account when developing the models. The harmonic model shall be determined in the positive- and negative-phase sequence. The model shall be a Thevenin equivalent.

The source and the impedance of the Thevenin equivalent shall be frequency-dependent.

- The Thevenin equivalent shall be given in increments of 10% P_{AV} between 0% and 100% active power infeed while the reactive power provision is varied between 0% $Q_{\mathrm{AC,max/min}}$, 50% $Q_{\mathrm{AC,max/min}}$ and 100% $Q_{\mathrm{AC,max/min}}$. This shall take into account the following:
    - Whole voltage operating range
    - The model shall consider the influence of the whole control, control modes (e.g., with and without active damping) and measurement system and other parts of

the converter which influence the output characteristics in the specified frequency range.
  - All passive elements of the plant (e.g., transformers, filters) shall be taken into account.
  - As addition the frequency-dependent control characteristic as well as the characteristics of the passive elements shall be provided separately.
  - Possible switching configurations (e.g., closing and opening the switchable impedance of the OWF)
  - The model shall encompass the 95% and 100% quantiles of the converter's harmonic voltage emissions.
  - The model shall include the phase angle of each harmonic (dominant angle and dominant angle ratio).
  - The model shall include all feed-ins of interharmonics and harmonic emissions with amplitudes above 0.2% of the grid reference voltage in the frequency range up to 9 kHz.
  - The OWF operator shall specify and justify simplifications made in the calculation of the OWF output impedance.
  - Impedance (amplitude and phase) may be calculated using one of the following methods or an equivalent method:
    - Transfer functions describing the corresponding systems and equipment
    - Numerical calculations

2.2.4.1 VALIDATION

The frequency-dependent impedance and emission provided in the harmonic model shall be validated by at least one of the following models.

- EMT model
- Test results of the factory test (real-time simulations with the actual control implementation) or
- Analytical model

Validation shall be performed for all given frequency-dependent impedance curves. The harmonic emission shall be validated for all given operating points in the model.

3 SIMULATION STUDIES

The OWF operator shall conduct the studies listed in Annex B of the grid codes VDE-AR-N 4131 to prove grid codes compliance. In addition, following studies are to be performed:

1. Grid Forming Capability in accordance with the FNN Guideline Grid forming behaviour of HVDC systems and DC-connected PPMs
2. Interaction study in the frequency domain as Screening at the network connection point (66kV or 132kV)
3. Interaction study in EMT at the network connection point (66kV or 132kV)

The TSO shall provide a representation of the network at the grid access point to the OWF operator via the annex “Grid Data delivered by the TSO”.

Models shall only be used in studies once approved by the TSO. All assumptions made, model simplifications and settings shall be documented and shall be described in detail. The OWF operator shall demonstrate and document the equivalent functionality and suitability of a simplified model and shall submit these for checking and approval promptly before the TSO studies begin.

The respective model used shall be supplied with each version of a study to enable the TSO to replicate the study results. The scenarios shall be uniformly and straightforwardly identified in all documents and annexes to allow for clear classification.

The simulation results of all simulation scenarios shall be provided as Comtrade files as well as PDF files.