REQUIREMENTS REGARDING THE PROVISION OF EMT SIMULATION MODELS

Harmonised EMT model requirements for HVDC and STATCOM

Table of Contents

1 Introduction

The behaviour of a power electronics system at a grid connection point is largely tested by means of simulation, using various software tools. As control has a major influence on system behaviour, a realistic simulation of the system and simulation results of sufficient quality can only be ensured if the original control software is integrated into the simulation environment used. Furthermore, alongside an appropriate description of the power unit, independence from a specific simulation environment must also be guaranteed. Modelling of control software in a specific simulation environment runs the risk of modelling errors, proprietary model components, inadmissible simplifications and so on, and is not permitted.

Every power electronics system consists of components that fall into one of the following three groups for simulation purposes:

- **Power unit:**

  The power unit comprises electrical, magnetic and mechanical components such as transformers, converter hardware (including semiconductors, filters, sensors/transducers) and switchgear.
- **Control hardware:**

  The term 'control hardware' covers all hardware that is not located in the power unit and is used, for example, for the control, regulation or protection of the system. These can be digital systems such as industrial PCs or electronic assemblies with microprocessors, digital signal processors or FPGAs. Analog controls also fall within this group.
- **Control software:**

  The control software group essentially includes the software run on the associated control hardware and that realises the desired control function. This applies, for example, to the software for controlling the converters or the software for generating the pulses for the active semiconductor valves. This group also encompasses control software, protection software and software for simulating the function of drive actuators that are controlled on the system without software (e.g. analog protection systems whose function is replicated in the simulation with control software).

The overall control can have any structure in which different tasks are executed with different function modules (e.g. based on DSP, FPGA) in different sampling times (see Figure 1). The function modules can be connected to each other and to the power unit as required. They are connected to the power unit, for example, for measurement signals via analog transducers, whose real properties such as filter characteristics or delays can influence the control behaviour. To ensure adequate simulation models, the overall control must be modelled according to its effect.

Unless otherwise specified by the client, as a rule the following shall apply:

- The modelling of the control systems, the integration of the control algorithms and the modelling of the power unit must be strictly separated from each other.
- Compiled code shall be used for the integration of the control algorithms per function module and the corresponding interfaces between the function modules within the control system or the power unit must be sufficiently documented. (NB: deviations/simplifications are possible in this regard after consultation with the client, see Section 2.2.3).
- The power unit and the control systems shall be modelled in the specified simulation software. The modelling of the control system must ensure that the control algorithms are called correctly within the required sampling times. The sampling time can vary and depends on the control algorithms used (e.g. with frequency-synchronous sampling).

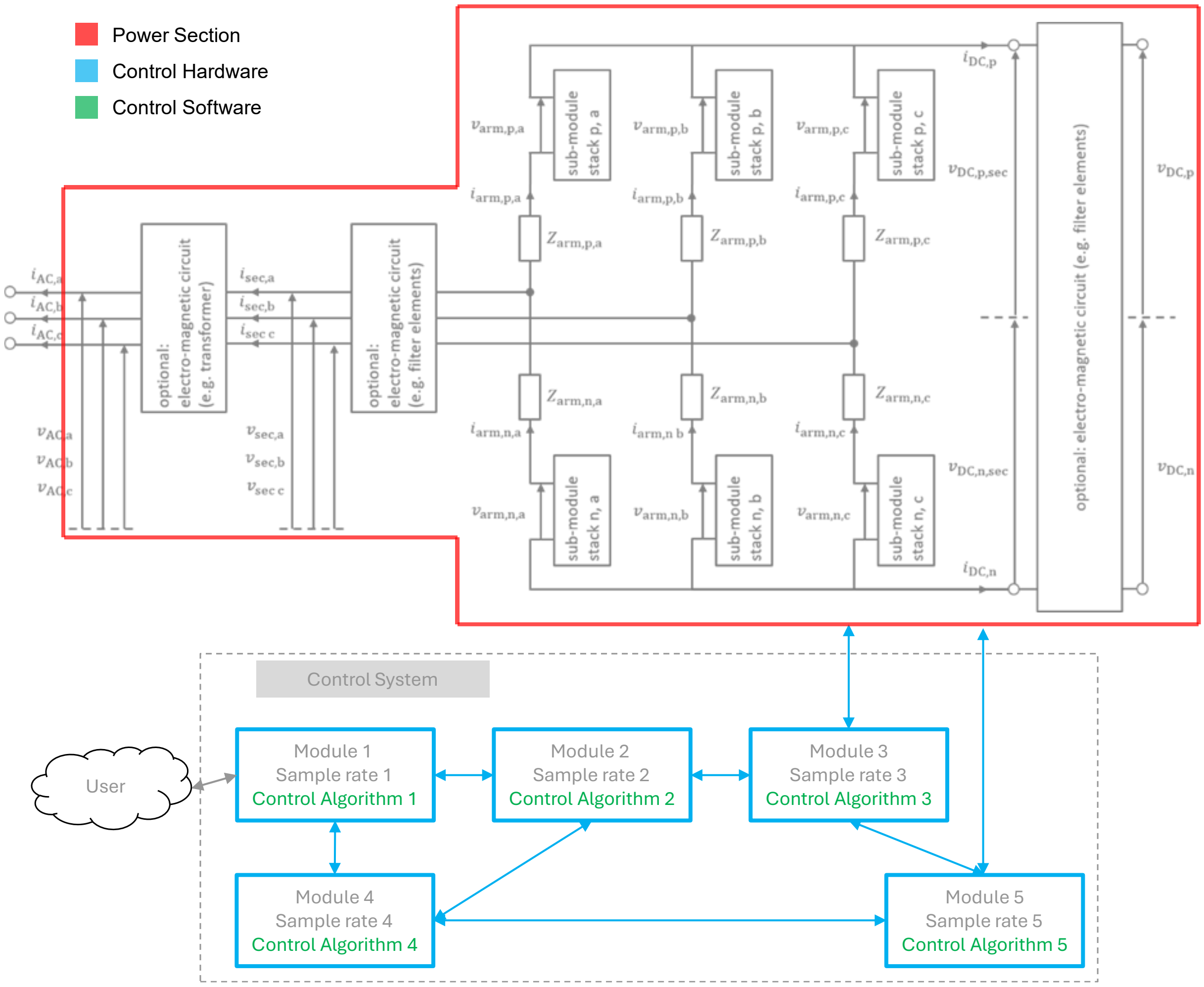

Figure 1: Example of a control system consisting of five function modules with different sampling rates

2 Requirements regarding the provision of models and data

2.1 General

The models to be provided by the contractor and the necessary level of detail depend on the phenomenon to be analysed and the question at hand. As a rule, models must be provided that reflect the behaviour of the system during steady-state, dynamic (RMS) and transient (EMT) processes, including harmonic and interharmonic components.

In particular, the models serving as a basis for the studies carried out by the contractor as part of the design and engineering phase must also be provided so that the results of these studies are comprehensible and reproducible.

The requirements regarding the provision of data and models are described in more detail below in accordance with the aforementioned groupings (power unit, control hardware, control software).

2.2 Tool-independent provision of data and models

2.2.1 Power unit

An equivalent circuit diagram comprising all power unit components, the associated parameters (with test records and data sheets if required) and all measuring points and actuators (switches) must be provided for the power unit. The equivalent circuit diagram and the documents must encompass all components relevant to the functionality of the system. The equivalent circuit diagrams and parameters must be valid for the frequency range specified by the client.

These include:

- transformers;
- filters;
- arresters;
- converters (inductances, capacitances, semiconductor properties);
- braking controllers, if applicable;
- neutral point connections;
- earthing resistance;
- connection lines (overhead lines, cable systems);
- switches (AC and DC side).

See Section 3 for more information.

2.2.2 Control hardware

The control hardware essentially records the measured variables, executes the associated control software and issues the associated output variables. This process is repeated cyclically depending on the sampling times. To reproduce this behaviour in the simulation, the following data must be specified for each function module (e.g. CPU, DSP) of the control hardware:

- Assignment of the input variables: a tabular list of the input variables of the control hardware must be provided. Input variables comprise, for example, the measuring points of the power unit or the output variables of other function modules of the control hardware.
- Assignment of the output variables: as with the input variables, a tabular list of the output variables must be available in order to be able to assign them to the inputs of other control hardware or the actuators of the power unit, for example.
- Assignment of the control software to be executed: each function module of the control hardware executes exactly one control software. As such, the associated control software, including the sampling rate/time, must be known for every control hardware. The interfaces to the other control hardware and the associated communication times must also be specified.

2.2.3 Control software

The control software may only contain the control algorithms (no electrical components!) in the form of one or more dynamic libraries (e.g. DLL files for Windows-based systems) with the defined interfaces. The control software must be provided as a compiled library for each physical control system/function module. A 32-bit and a 64-bit version must be created.

Unless otherwise requested by the client, compiled libraries for Windows-based systems (i.e. DLLs) are to be provided by default.

If the entire system control or the control system consists of several control systems, the compiled libraries must be submitted with a unique name for each control system. The use of several libraries within a physical control system and that are able to access each other is not permitted. The use of interpolation algorithms within the libraries, which are tailored to the simulation time step and the solver in specific simulation environments, is also not permitted.

In many cases, the control software (control algorithms) is already available as C code due to the development environment used or can be generated as C code through input in a block diagram and used, for example, in compiled form on an industrial PC to control the system. In this case, the original C code must be used directly to generate the compiled library. Simplification is not permitted.

Part of the system control is often not implemented in C code (such as pulse pattern generation, which is executed in an FPGA). In this case, the respective functionality must be implemented in C code and also generated as a compiled library with the specified interface.

Extensions of the control functions compared to the real system are not permitted. This particularly concerns the implementation of FPGA in the control system, which can for instance contain filtering of the measured variables.

Please note:

- If there are a lot of control systems (e.g. >10), in consultation with the client the control software can alternatively be subdivided into individual libraries or some libraries can be merged. The subdivision must be based on the control levels of the real system, e.g. pulse pattern generation separated from the converter-related control and from the superimposed control.
- In particular, the client and the contractor must agree on:
    1. which signals must be issued from the library as observable outputs;
    2. which functional control components (e.g. POD or active filtering) must be able to be activated/deactivated within the libraries.

The contractor must provide the following documents:

- Equivalent circuit diagram and parameters for the power unit
- Control software for each control system as a compiled library including comprehensive documentation regarding the interface definition used
- Documentation of the sampling rates and call sequence of the individual compiled libraries

As a rule, the provision of data (e.g. equivalent circuit diagrams, parameters for the power unit, information on the control system) and the control software provided in the form of compiled libraries, including the associated documentation of the interfaces, must enable the client to independently implement a model of the power electronics system in any simulation software using different software interfaces. The contractor must provide all information required to this end in machine-readable format (e.g. Excel).

The aforementioned procedure means that the data provision for the simulation of the power electronics system is tool-independent.

2.2.4 Software interfaces

The client specifies the software interface for the compiled libraries of the control software. The requirements regarding the interfaces and functions are specified here in the form of a C code header.

Regardless of the specific design, structures consisting of data vectors and/or data arrays are defined in each software interface, which are transferred to or returned by the individual functions in order to enable standardised data exchange between the control algorithms and the grid calculation program. In addition to these structures, the relevant functions required for the simulation are also defined. This includes, for example:

- the initialisation function;
- the calculation function, which is called cyclically during the simulation;

  NB: the call of the calculation function must correspond to the control cycle of the real control hardware and may not be constant (e.g. with a fixed sampling rate per grid period and variable grid frequency). The call must be controlled by the simulation environment used. The user must be able to flexibly adjust the simulation step size.
- the closing function, which frees up the memory space that was allocated in the compiled library;
- the reset function, which returns the control software to the state it was in after initialisation;
- the snapshot function, which makes available the internal (state) variables of the control to the software environment and so enables a snapshot to be taken;
- others, if applicable.

There are various available and well-known software interfaces, which differ in detail but are essentially suitable for integrating the compiled libraries into different simulation environments:

- ***IEEE/CIGRE Modelling Method***
  [Reference: IEEE-CIGRE B4.82 - Use of Real-Code in EMT Models for Power System Analysis]
- ***ENTSO–E Standardized Control Interface for HVDC SIL/HIL conformity tests***
  [Reference: https://www.entsoe.eu/2020/04/24/entso-e-standardized-control-interface-for-hvdc-sil-hil-conformity-tests/]
- ***IEC 61400-27-2:2022-08, Annex G***
  [Reference: DIN EN IEC 61400-27-2 (VDE 0127-27-2):2022-08, Annex G

Unless otherwise requested by the client, the contractor shall apply by default the ***IEEE/CIGRE*** standard for the libraries to be compiled for the individual control systems.

Irrespective of the choice of software interfaces mentioned above, the following must be taken into account:

- The returned data vector of the calculation function of the compiled library must contain the call time, which specifies the time or the duration until the next call of the calculation function and can be variable.
- Multiple instantiation of the compiled libraries in the simulation environment must be possible.
- Different compiled libraries must not share a memory area. Depending on the definition, internal memories may be required to persistently store control values (states) so that they can be reused in the next control calculation. To this end, memory areas may be reserved in the compiled library and used in the calculations. These memory areas must be explicitly assigned to the individual libraries. Shared access to the memory area by several libraries or instances is not permitted. The transfer of signals between different compiled libraries is only permitted via the defined interface.
- Snapshot functionality is required to save and load a control state. These functions make it possible to simulate various events from a defined starting point (defined operating point at a defined grid status). To do this, the internal (state) variables of the control must be made available to the software environment via the software interface. To protect the contractor's IP, encryption of the internal state variables of the control is permitted.

Regular updates of the control software to be supplied (compiled libraries) must be provided in accordance with the engineering development status. Lastly, the compiled libraries must be delivered with the control code that is implemented on the system. It must also be ensured that the compiled libraries can be integrated into corresponding simulation environments for the entire service life of the system. As such, a technical time limit for the libraries is not permitted.

2.3 Tool-dependent provision of data and models

The requirements set out in Section 2.2 must also be met for the tool-dependent provision of data and models. Tool-dependent models shall be provided in a simulation environment specified by the client (e.g. PSCAD, PowerFactory). In this regard:

- the power unit must be modelled in accordance with the associated data sheets/test records in the specified simulation environment;
- the control algorithms must be integrated into the specified simulation tool in the form of compiled libraries in accordance with the specified software interface using tool-specific wrappers;
- the simulation tool/wrapper must ensure that the control algorithms are called in accordance with the actual sampling rates of the control systems;
- the connection of the libraries and the wrappers must be made visible (no precompiling);
- no elements shall be implemented in the open model part that are originally located in the control software of the system.

The client may provide a template of a tool-dependent EMT model into which the compiled libraries must be integrated. If a template is not provided or if a simulation environment is explicitly specified, the EMT models must be supplied in PSCAD/EMTDC. The PSCAD version to be used must include at least V4.6.3 and V5. The tool-dependent parts of the model must be computable with Intel Fortran Compiler XE 15 and Intel Fortran Compiler 19. If the contractor uses other Intel Fortran Compiler versions in-house, a comparison of simulation results with the supplied Compiler version must be carried out and made available to the client. The tool-dependent model must be executable with Visual Studio versions 2012, 2015 and 2022. Should use of other versions of Fortran Compiler, Visual Studio or PSCAD be beneficial from the client's or contractor's point of view or become necessary over the course of the project, this can be adapted in consultation with the client.

3 Information about the scope of models and the level of detail of modelling

3.1 Basic requirements

As described in Section 2, the required model scope and level of detail of modelling depend on the dynamics to be analysed and the question at hand. The contractor shall provide the client with a (detailed) EMT model and a simplified EMT model. The key minimum requirements in this regard are listed below.

<u>Power unit: general</u>

- The model must take into account the detailed converter design. This includes:
  - the number and electrical parameters of the submodules and arm chokes;
  - all components of the converter stations (transformers, filters, surge arresters);
  - circuit breakers;
  - neutral point connections.
- If several parallel converters are planned, the EMT model must include the parallel-connected converters and the real pulse pattern generation of all converter units.
- If the power electronics system is connected via cable sections (on the EHV or MV side), the frequency-dependent transmission behaviour of the cable systems must be simulated using

suitable EMT models in accordance with the specified frequency range and must be verified by the contractor in a suitable form.

- The frequency-dependent transmission behaviour of the EHV/MV transformer must also be simulated in accordance with the specified frequency range. Adequate modelling of the transmission behaviour of the transformers must be verified by the contractor by means of comparison with measurement data. In addition, the saturation properties of the transformers must be suitably modelled and compared using measurement data
- **Frequency range:** the model must be valid within a frequency range of 0 Hz to 2,500 Hz. Moreover, the EMT models must be suitable for analysing slowly varying overvoltages for an extended frequency range of 0-20 kHz. The contractor must document any modelling restrictions that may occur due to the extended frequency range.

Power unit: converter

- The EMT model must reflect the currents and voltages of the submodules, switching energies of the semiconductors, i.e. including the non-linear properties, and so on. The idle periods between the on and off status of the IGBTs must be modelled.
- The EMT model must also take into account the junction temperature-dependent semiconductor properties such as on-state voltages, switching losses and recovery losses.
- The number of active modules (function and submodules) must be adjustable by the user within the range of the minimum necessary and maximum available modules (redundancy).
- The EMT model must reflect the actual state of the system with regard to the submodules, operating equipment, parasitic elements, and so on.

Control and protection of the power electronics system

- All details of the converter control (e.g. internal and external control loops) and the triggering of the power electronics and converter protection must be included.
- All control and protection systems (measurement recording, superordinate control, converter-related control, triggering of the power electronics, protection functions) must be included in the EMT model and described in detail in the associated documentation.
- All essential control and protection functions, but as a minimum those functions necessary for the proof of conformity of the electrical properties as per VDE-AR-N 4131, must be part of the EMT model and must be able to be switched on/off and configured.
- The EMT model must reflect the real control behaviour and realistic behaviour in terms of measurements, dead time and signal transit times, interlocking times and so on. This must be documented.
- The EMT model must encompass all the required functions that are active/effective in the frequency range specified for this model.
- The EMT model must simulate the real start and switch-off behaviour of the control and the converter.
- Additional stability and modulation functions, e.g. AC voltage control, frequency control, power oscillation damping (POD) control and the EPC function (if applicable), must be fully accessible and configurable.
- The EMT model must contain a sufficiently detailed simulation of the relevant protection functions, taking into account delay times in the measurement, signal processing and communication system as well as the non-linear behaviour of instrument transformers. In particular, all protection functions that are necessary for the direct protection of the converter units must be implemented. These must be specified and described in full, including their trigger values. The following applies as a minimum:

a. Built-in switching sequences relevant for the time domain
b. Relevant fault locations must already be implemented and be selectable by the user. Additional fault locations to be analysed can be defined by the client during the project and must be subsequently integrated into the EMT model.
c. The following protection parameters must be included as a minimum and must be adjustable, if necessary:
    - Undervoltage and overvoltage
    - Frequency
    - Overcurrent
    - di/dt
    - Harmonics
    - Current or voltage imbalances

Intended purpose

- The EMT model must be able to carry out the system studies required as part of the process for complying with the grid connection conditions.
- The EMT model must ensure the traceability and reproducibility of the results of the design studies.
- For HVDC: the EMT model must depict the behaviour of the system in case of short circuits on the DC line, including protective measures, reconfiguration and automatic reclosing (if applicable).
- The dynamic libraries must — if required by the client — also be capable of running on real-time systems (to be defined by the contractor) and be usable for Hardware-in-the-Loop (HIL) tests.

Documentation and operation

- Parts of the EMT model that represent the controls at grid and station level must be disclosed. If these are encrypted for unavoidable reasons, block diagrams describing the controls in full, including the parameters used, must be provided as an alternative.
- Converter-related controls must be described and block diagrams that detail the key properties and connections must be provided.
- The parameters that can actually be set by the client must also be accessible and adjustable in the model.
- The user must be able to flexibly adjust the simulation step size of the EMT model.
- In the EMT model, the user must be able to recognise which protection functions, including the exact ID/number, have been triggered.

3.2 Simplified EMT models

In addition to the detailed EMT model, a simplified and possibly aggregated EMT model representing a compromise between modelling depth and computational effort must also be provided for the simulation of the power electronics system in tool-dependent format.

The detailed EMT model of the system contains the fully modelled (possibly parallel) converter units including real pulse pattern generation. The requirements specified in the previous sections must be met. The detailed EMT model is used, among other things, for benchmarking against the simplified EMT model and the real-time simulation models as well as for detailed design and interaction studies.

The simplified EMT model of the system can consist of a simplified arm or valve modelling of a converter (e.g. simulation of the converter arms using equivalent voltage sources) and does not take pulse pattern generation into account. The control determines the desired phase control factor for each arm and sets the arm voltage in the equivalent voltage source based on the phase control factor and the current capacitance voltage. Parallel converters can be aggregated in the case of identical hardware and identical control. With regard to analysis, simplified EMT models are primarily used for extended EMT system studies. The simplified EMT model is validated by means of benchmarking against the EMT model.