HVDC-WISE D4.3 Library of models

HVDC-Wise lib

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Executive Summary

This report provides a comprehensive overview of the **HVDC-Wise lib**, a GitHub repository containing a collection of HVDC equipment models designed to facilitate standardized model exchange. The library, available at https://github.com/HVDC-WISE/HVDC-Wise_lib, adheres to the IEC CIM/CGMES standard format, offering models split into *static* and *dynamic* parts, along with the complete model documentation. The static part includes data like model topology and equipment parameters, while the dynamic part focuses on the mathematical equations and artifacts and is often representing behaviour of control systems. The approach used to develop the models in the library are described in another deliverable of the project (D4.2 "Technology modelling").

The report covers the following key aspects:

- **Library Structure**: The HVDC-Wise lib is organized into three primary sections: data exchange specifications (for static data), artifacts and equations exchange (for dynamic equations), and documentation (supporting files for model integration).
- **Use Cases**: The library caters to a variety of users—those exploring HVDC models, integrating models into applications, and standardizing models for broader use. Depending on the compatibility of tools, users can download and apply models in MATLAB language, functional mock-up unit (FMU), Modelica code, or CIM-based representations.
- **Contribution guidelines**: The report details the contribution process, including submitting new models to the library, documentation requirements, and steps for pull request review and approval.
- **Model documentation:** The report provides documentation for each of the library models, using a unified template. The models included into the initial release of the HVDC-Wise lib are grid-following inverter (connected to an ideal DC source), a chain link of submodules with energy storage connected to DC terminals, a modular multilevel converter (MMC) for HVDC applications, and a DC/AC voltage sourced converter (VSC).

HVDC-Wise lib is released under the European Union Public Licence v. 1.2 (EUPL), an open-source licence. This supports the ongoing standardization efforts for dynamic-model exchange in HVDC equipment, with a long-term goal of enhancing interoperability and collaboration across the energy sector.

1 Introduction

The increasing complexity of modern energy systems, particularly with the rise of High Voltage Direct Current (HVDC) technology, has created a pressing need for standardized methods to exchange models and data related to HVDC equipment. Also [1] highlighted the need for dynamic security and dynamic resilience assessments during the planning process. Efficient exchange of both the static data (such as model topology and equipment parameters) and dynamic models (such as mathematical model equations) is critical for seamless integration and interoperability across different tools, platforms, and stakeholders. For further implementation of the methodology proposed in the HVDC-WISE project [1], it is then necessary to check that existing standards are sufficient to exchange models including dynamic behaviours and to propose evolutions of standards if needed.

For this, the HVDC-WISE project firstly proposed a workflow [2] to develop HVDC equipment models based on the IEC Common Information Model (CIM), specifically the newest edition of IEC CIM for Dynamics (IEC 61970-457:2024), and the IEC Common Grid Model Exchange Standard (IEC 61970-600-1, IEC 61970-600-2). These models facilitate the standardized exchange of data and equations, thus ensuring that models can be shared, analysed, and implemented across various environments. Secondly, **HVDC-Wise lib**, a library of such models has been developed. Thirdly, recommendations for extension and improvements will be drawn in a further deliverable (D8.3).

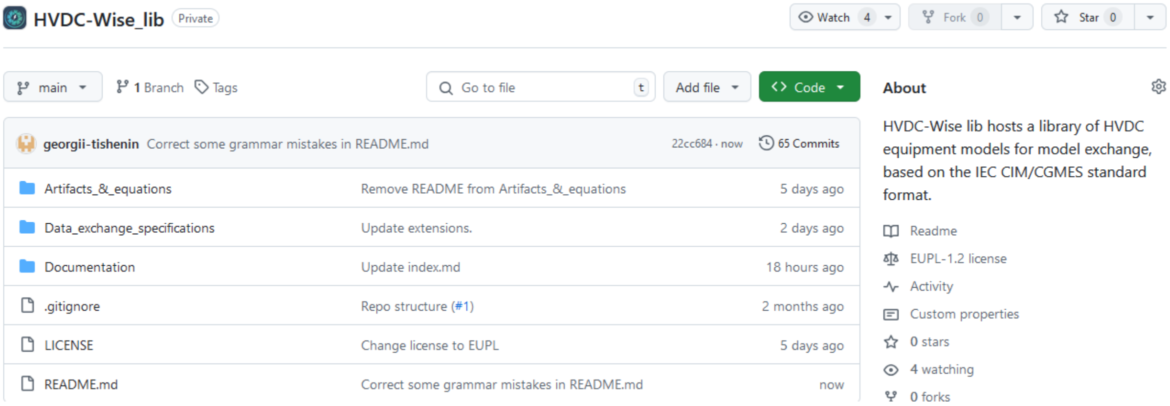
This report describes **HVDC-Wise lib**. This repository can be accessed in https://github.com/HVDC-WISE/HVDC-Wise_lib and models are shared under the European Union Public Licence v. 1.2 (EUPL), an open-source licence. **HVDC-Wise lib** does not only allow to assess the readiness and limitations of existing standards for dynamic studies include HVDC equipment but also, to test the implementation of the workflow proposed in [2], to release models useful for the community working on power system modelling and to offer a repository to host additional models from various contributors.

It includes presently models that have been selected to test different aspects of modelling that are needed for the development of hybrid AC/DC systems. This includes capability to model dynamic behaviours either through equations (in MATLAB or Modelica languages) or through black-boxed models (thanks to the functional mock-up interface [3] standard). It includes also the capability to describe new devices connected to DC terminals. The library's two-part structure, dividing models into *static* and *dynamic* parts, ensures that both equipment data and control behaviour are captured and made available for exchange. There is, however, a deviation, compared to the list of the building blocks, identified in [4]. The reason for the deviation is that some of the building blocks, identified in [4], are already available in IEC CIM, such as *DCLine* or *DCBreaker*. Other building blocks, such as DC/DC converters are not required in HVDC-WISE Use Cases. As the library will be open source, there is no limitation to extend it with further models after the release of this report.

This report outlines the library structure (section 2), its usage (section 3), and how to contribute (section 4). In section 5, for each model, the same organisation is used: context; model use; assumptions, validity domain and limitations; model description and eventually model exchange. This last topic emphasizes its role in promoting the standardization of HVDC equipment models. The presented models are a grid-following inverter (connected to an ideal DC source) in sub-section 5.1, a chain link of submodules with energy storage connected to DC terminals in sub-section 5.2, an MMC for HVDC applications in sub-section 5.3 and a DC/AC VSC in sub-section 5.4. Eventually, conclusions are drawn in section 6. Details on the lessons learned and needed extensions are in [2] and recommendations for standardization will be considered in a further deliverable (D8.3).

2 Library Structure

Figure 2.1 shows the structure of **HVDC-Wise lib**. **Data_exchange_specifications** contains proposed extensions to IEC Common Information Model (CIM) and profiles to support data modelling and exchange of the *static part* and the *dynamic part* of the library's models. **Artifacts_&_Equations** contains all relevant information categorized per model type. Here, the user will find artifacts and equations that can be used to realize the exchange of the *dynamic part* of the library's models. **Documentation** contains documentation for the library models and resources, supporting documentation (e.g. **Images** or **Templates**). This is the place to explore first and get familiar with models that are included in the library. In the description of each of the models' parts of the library, the user will find information about available open-source implementations and artifacts.



georgii-tishenin Correct some grammar mistakes in README.md 22cc684 · now 65 Commits

Artifacts_&_equations	Remove README from Artifacts_&_equations	5 days ago
Data_exchange_specifications	Update extensions.	2 days ago
Documentation	Update index.md	18 hours ago
.gitignore	Repo structure (#1)	2 months ago
LICENSE	Change license to EUPL	5 days ago
README.md	Correct some grammar mistakes in README.md	now

HVDC-Wise lib hosts a library of HVDC equipment models for model exchange, based on the IEC CIM/CGMES standard format.

FIGURE 2.1 STRUCTURE OF HVDC-WISE LIB

3 Usage

The library supports multiple formats for *dynamic part* of the model to ensure long-term interoperability. The usage of the library, i.e., importing and using models in applications or standardizing the models can give feedback and further enhance the quality of the library. The library accommodates several use cases, discussed further below.

Exploring Models

Users who would like to get knowledge on the way of exchanging information using IEC CIM can find real-life examples. To learn more about a specific model refer to model documentation.

Using Models in Applications

Users who would like to integrate models in their environment can download and use models in different tools depending on the compatibilities. To use a model in their application, users need to check if the model is available in a suitable format for the application. The library includes several formats for *dynamic part* of the model, such as code in MATLAB language, functional mock-up unit (FMU), Modelica code, or CIM-based representations. Since not all models are available in all formats, integrating a model into an application may require manual adjustments. This could involve ensuring compatibility of *static part* or embedding *dynamic part* of the user-defined model within the application. As vendors implement better import functionalities, the integration process will become more streamlined.

Standardizing Models

If the user is interested in standardizing a model for use in the scope of an association, project, study or at international standard, it is recommended to study all the details and even approach the main contributors for a given model. HVDC-WISE is taking an initiative to disseminate and promote the deliverables for standardization.

4 Contribution Guidelines

The guidelines to contribute a model to **HVDC-Wise lib** are presented further below.

Open an Issue

Start by creating a new issue in **HVDC-Wise lib** GitHub repository to propose your model.

Prepare the Contribution

Create a new branch (e.g., `*model-name*`) and begin working.

The contribution should include:

- Model documentation using the template, provided in **HVDC-Wise lib**.
- *Dynamic part* in one of the supported formats:
    - Code (Modelica or MATLAB).
    - Artifact (FMU).
- CIM Extensions (if modelling *static part* requires to extend CIM).

Figure 4.1 shows a workflow to contribute a model to **HVDC-Wise lib**.

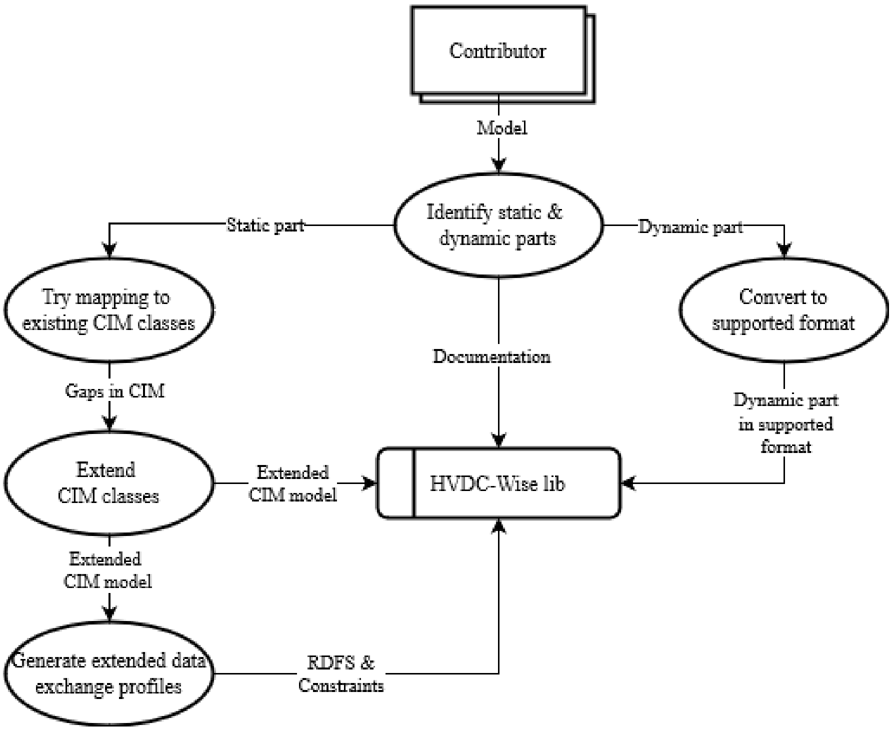


FIGURE 4.1 WORKFLOW TO CONTRIBUTE MODEL

Submit a Pull Request

When your contribution is ready, create a pull request (PR) to merge your branch into the main branch.

Review and Merge

Your PR will be reviewed by a maintainer. Once approved, your contribution will be merged into the main branch.

5 Model Documentation

Table 5.1 lists the models included into the initial release of the **HVDC-Wise lib**. The grid-following inverter, HVDC MMC and voltage source converter are all models of the HVDC converters. The difference between these three models is in the modelling domain of the original model implementation, language describing dynamic equations (Modelica or MATLAB) and modelling depth: grid-following inverter is the model with the lowest modelling depth, as it assumes an infinite power source connected at the DC side of the converter, not allowing to connect the model in the DC side of the grid, and has a very simple generic grid-following control architecture. Voltage source converter is the model with intermediate modelling depth, interfacing the AC and DC systems. HVDC MMC model has the highest modelling depth, due to detailed representation of control modules, as mentioned in Table 5.1. The subsections below describe all the models in more details.

TABLE 5.1: CONSIDERED MODELS

NAME	DESCRIPTION	PROJECT PARTNER	DOMAIN
Grid-following inverter	Average value inverter model with positive-sequence grid-following control	RWTH	EMT
HVDC MMC	HVDC MMC model with detailed representation of control modules: synthetic inertia, frequency sensitive mode, power oscillation damping, P/Vdc control, Q/Vac control, voltage unbalance control, fault ride through.	TenneT TSO GmbH	RMS
DC energy storage	Model of a chain link of energy storage submodules	Supergrid Institute	EMT
Voltage source converter	Generic voltage source converter HVDC model for power system stability studies	RWTH	RMS

5.1 Grid-following inverter

5.1.1 Context

An electromagnetic transient (EMT) average value grid-following inverter model, described in [5], was developed and implemented in ModPowerSystems[1] and in DPsim[2] by RWTH Aachen University, Germany. The EMT model was developed to serve as a benchmark in studies to compare simulation accuracy, numerical stability, and performance against dynamic phasor (DP) model in large-scale grid simulations. According to the classification given in [6], the model corresponds to Type 6 computational model.

5.1.2 Model use, assumptions, validity domain and limitations

The model can be used for transient stability analysis and for testing frequency control techniques. Assumptions and limitations include:

- Average value model. The voltage source interface of the model does not allow to represent switching harmonics.

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[1] https://github.com/ModPowerSystems/ModPowerSystems

[2] https://github.com/sogno-platform/dpsim

- Positive sequence model. The control architecture of the model contains only one phase-locked-loop (PLL) and can correctly track the voltage angle in simulations of symmetric grids only.
- Infinite power model. No primary energy source or storage is modelled, the output power of the model is not limited by physical constraints.

5.1.3 Model description

The EMT average value grid-following inverter model includes electrical circuit, control system and interface connecting the former two, as shown in Figure 5.1.

The EMT model electrical circuit is described with time-domain differential equations in *abc* stationary reference frame and includes:

- A controlled voltage source. The controlled voltage source represents the inverter's output based on an averaged switching model.
- An LC filter (as an output filter), which is composed of two resistors, an inductor and a capacitor.
- (Optionally) a step-up transformer.

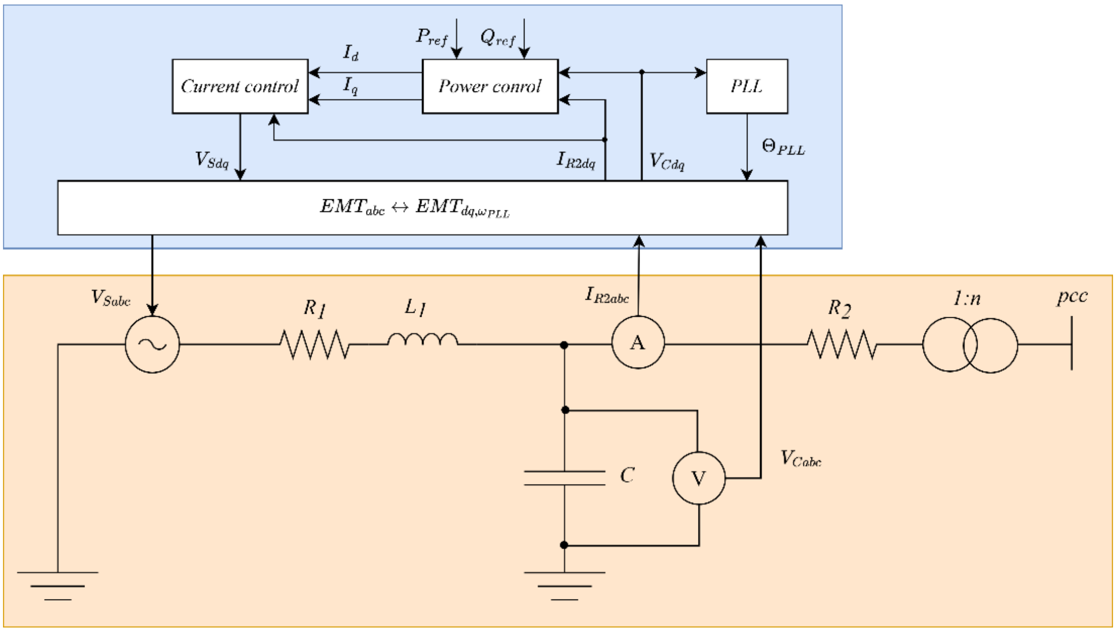

FIGURE 5.1 GRID-FOLLOWING INVERTER DIAGRAM

The control system of a grid-following inverter is designed to deliver active and reactive power according to specified reference values P_{ref} and Q_{ref} to an energized grid. The equations of the control system are in the inverter's local *dq* reference frame. The control system includes:

- A PLL. The purpose of the PLL is to synchronize the rotation speed of the inverter's local *dq* reference frame with the frequency of the measured voltage V_{Cabc} and align the axes of this *dq* reference frame with the angle of V_{Cabc}. The PLL includes a PI controller, that drives the *q* component of the V_{Cdq}voltage to zero using a feedback control loop. The loop is formed by PLL and Park transformation in the *abc* <-> *dq* interface.

- A power control. The power control involves power calculation from I_{R2dq}, V_{Cdq} and a PI controller, regulating I_d and I_q to meet the specified reference values P_{ref} and Q_{ref}.
- A current control. The current includes a PI controller, regulating the setpoint V_{Sdq} for the controlled voltage source in accordance with the reference currents I_d and I_q, provided by the power control.

Transformation of signals between the EMT grid-following inverter's electrical circuit in *abc* reference frame and control system in *dq* reference frames is done with Park and inverse Park transformations, using the angle θ_{PLL}.

5.1.4 Model exchange

The static part of the grid-following inverter model includes the electrical circuit, that can be mapped to *EquivalentInjection* in CIM and does not require extensions to CIM. The dynamic part of the grid-following inverter model includes the control system and the interface. The dynamic part of the model is serialized in CIM XML file using the *DetailedModelConfigurationProfile* of IEC 61970-457:2024 [7], as well as Modelica code. The CIM model includes classes needed to exchange the dynamic model configuration, i.e. the structure and connectivity of a detailed model, whereas the Modelica code includes equations which explicitly describe the model dynamics.

From the practical model exchange point of view, e.g., for model import into PowerFactory 2024, the static part of the model can be imported using CGMES versions 2.4.15 or 3.0. However, the dynamic part relies on the *DetailedModelConfigurationProfile* [7], which is not yet supported by PowerFactory 2024. Currently, the dynamic model, originally in Modelica, might be imported to PowerFactory 2024 as a Modelica model or an FMU. Full automation of this process would require updates to CGMES and PowerFactory to integrate the dynamic profiles from IEC 61970-457:2024 [7].

5.1.5 Open-source implementations

The Table 5.2 lists open-source implementations of the EMT average value grid-following inverter model.

TABLE 5.2: OPEN-SOURCE IMPLEMENTATIONS OF THE EMT AVERAGE VALUE GRID-FOLLOWING INVERTER MODEL

SOFTWARE	LANGUAGE	OPEN-SOURCE LICENSE
ModPowerSystems	Modelica	Modelica License 2[3]
DPsim	C++	MPL v2.0[4]

Electrical circuit of the model implementation in ModPowerSystems does not include resistor R_2 and step-up transformer.

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[3] https://modelica.org/licenses/ModelicaLicense2.html

[4] https://www.mozilla.org/en-US/MPL/2.0/

5.2 DC energy storage

5.2.1 Context

An energy storage system connected to HVDC terminals has been selected as an example of potential future equipment to be included in standardized model exchanges. This kind of equipment is currently at low technology readiness level (TRL), but there is an interest to disseminate models to allow system planners to assess benefits of such technologies [8]. The converter presented in [9] and in Figure 5.2 has been selected among the candidate technologies listed in section 2.5.2 of [4].

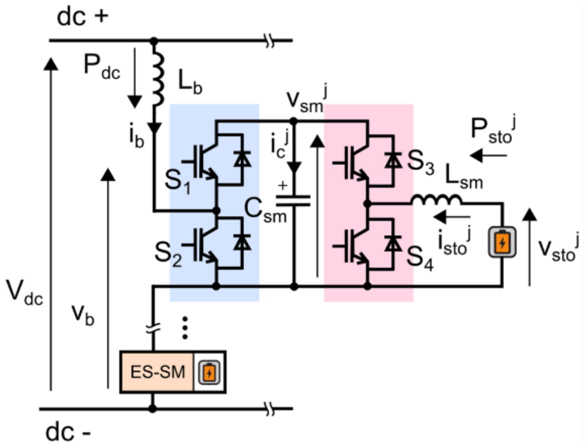

FIGURE 5.2 SCHEME OF THE DC CONNECTED BRANCH OF SERIES-CONNECTED SUBMODULES WITH ENERGY STORAGE

Modelling this DC-connected energy storage system allowed to highlight some gaps in existing CIM standards [10] and the possibility of representing the dynamic part by referencing a black box (compiled) model according to the FMI standard [3]. Indeed, as a control has been previously developed in MATLAB/Simulink (for EMT simulations), and as it would be time consuming to re-describe the scheme with Modelica equations, it has been decided to test the possibility of representing the dynamic part by referencing a black box (compiled) model according to the FMI standard.

5.2.2 Model use, assumptions, validity domain and limitations

As shown in Figure 5.2, the considered converter is made of the series connection of an inductor and several energy storage submodules (ES-SMs). These ES-SMs are half-bridge submodules (as in common AC/DC modular multilevel converters (MMCs)) with an additional dc/dc converter (S_3, S_4 and L_{sm}) interfacing the submodule capacitor and the energy storage elements. These energy storage elements can be batteries or supercapacitors. In each ES-SM, switches S_1 to S_4 are turned on or off to control the power exchange between the energy storage elements and the HVDC terminals and to balance v_{sm}^j, the voltages of submodule capacitors.

For system-level simulations, considering each switch, each capacitor, internal balancing algorithms, etc. brings an unnecessary complexity and an *average arm* modelling approach can be used as it has been done to develop DIgSILENT PowerFactory model of this converter in another task of the project and described in the repository documentation and in [2] as well. In such a model, the energy stored in all submodule capacitors is modelled with a single equivalent capacitor (C_{eq}) with an equivalent voltage v_c^b. The power absorbed by the chain of ESSMs is transferred to the equivalent capacitor

($v_b i_b = v_c^b i_{c,b}$). This is controlled by a modulation index m_b, modelling the average state of switches S_1 and S_2 in all ESSMs, and it can be shown that $v_b = m_b\, v_c^b$. The energy in the equivalent capacitor C_{eq} evolves also according to the power exchange with the batteries or supercapacitors, which are also modelled as lumped elements.

This model then relies on the hypotheses of balancing of voltages v_{sm}^j and identical ES-SMs. It cannot be used for instance for internal balancing studies or switching losses calculations. The model has not been designed to represent the behaviour in case of DC fault. The converter is made to operate with the sum of submodule capacitor voltages V_{sm}^i higher than V_{dc}, it is then possible to control the branch current in case of DC fault as in normal operation. In case of undervoltage, two possible behaviours are possible: controlling the branch current as in normal operation or blocking the converter. The first option can be used with this model provided the power reference P_{dc}^{ref} is limited to avoid over currents. The user should then use an undervoltage detection function to limit the DC power reference (and then the currents in the converter). If the converter is expected to be blocked in case of DC fault, after the detection time and blocking of switches, the fault current circulates through the diodes in switches S_2 without affecting submodule capacitors C_{sm}. As there is no submodule capacitor voltage inserted in the fault path, the fault current decreases until the inductor is completely discharged and the energy storage elements do not contribute to the fault current [9]. To model this behaviour, it would be necessary to add an undervoltage detection and, when triggered, set V_b (the voltage inserted by submodules) to 0V.

The model can be used to assess the impact of energy storage for grid stability[5] and derive specifications for this energy storage device.

5.2.3 Model description

The static part of the model includes only the elements connected to the DC terminals in Figure 5.2: the equivalent resistance and inductance of the inductor, and the controlled voltage source. The dynamic part defines v^b and includes the modelling of the energy storage elements and the energy stored in submodule capacitors.

The control is designed to regulate P_{dc}, the injected dc power and the energy in the capacitors of the ES-SMs. P_{dc} is controlled using switches S_3 and S_4, which in the average model corresponds to the duty cycle of the equivalent dc/dc converter, D_b. The energy in the equivalent capacitor is regulated with S_1 and S_2, which corresponds to the modulation index, m_b. The control scheme is extensively detailed in [9].

The control scheme and the modelling of the ES-SMs have been previously built in the MATLAB/Simulink environment. The dynamic part of the model is implemented thanks to the Function Mock-up Unit (FMU) standard [3]. The *fmu* file then includes the models for the supercapacitors, current control loops, energy on submodule capacitors, etc. This file is the same as the one used to model the converter in DIgSILENT PowerFactory. It has been created for in another task of the project as described in [2].

The main parameters of the model are listed in repository documentation and in another deliverable of the project [2] and are then not repeated here. Equations to calculate the model parameters are given in [9] and in [2].

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[5] For events like AC faults, converter trip, DC system reconfiguration and changes of operating points, but not for DC faults

5.2.4 Model exchange

As CIM-based data exchange currently requires concrete modelling of the static part of equipment models, several gaps in canonical CIM are identified.

First, relevant classes and attributes to model electrical circuit of DC energy storage are not available in current editions of the IEC standards. It was then necessary to propose new classes (see in folder *Data_exchange_specifications* of **HVDC-Wise lib**.) including a class *DCStorage* which has attributes like rated DC voltage, maximal power, number of submodules, series inductance. The submodules can be of two types (with batteries or supercapacitors) which are also described in proposed extensions with attributes including maximal energy, no-load voltage, capacitance.

The second identified gap is the limited capability of the standard to report DC state variables of DC terminals and nodes, i.e. in general there is a gap to report power flow results of the DC part of the model. Therefore, this gap was also covered by an extension.

5.3 HVDC MMC

5.3.1 Context

Generic models of multi-terminal HVDC systems, using modular multi-level converters for both symmetrical and asymmetrical RMS and EMT simulations, have been implemented in DIgSILENT PowerFactory by DIgSILENT GmbH for TenneT TSO GmbH [11].

5.3.2 Model use, assumptions, validity domain and limitations

The model can be used for transient stability analysis and for carrying out fundamental investigations on generic network models, as well as to assess potential network expansions with multi-terminal HVDC systems with regard to the electrical behaviour.

Assumptions and limitations include:

- To emulate the power converter (converter), the DIgSILENT PowerFactory internal element "PWM Converter" is used. The HVDC converter technology considered in the model is modular multi-level Converter (MMC). The models can be used for both half-bridge and full-bridge MMC technologies.
- The converter models for load flow calculation, RMS-simulation and the Controlled voltage source model for EMT-simulations are based on a fundamental frequency approach.
- The PWM converter losses are specified in the fundamental frequency models as the sum of:
    - No-load losses: specified with the parameter Pnold in [kW].
    - Switching losses: specified with the parameter swtLossF actor in [kW/A].
    - Resistive losses: specified with the parameter resLossF actor in [Ohm].
- The measurements at the neutral points of the DC network must be based on the same reference voltage as the measurements at the positive and negative terminals.

5.3.3 Model description

The model includes the following components:

- HVDC converter
  - The MMC model is based on the topology shown in Figure 5.3. The model allows selection of half-bridge cell or full-bridge cell for the sub-modules (SM).
- HVDC transformer
  - The transformer connects the DC grid to the high-voltage AC transmission grid.
- DC chopper
  - DC choppers (braking resistors, also known as energy dissipating system) can be added in the converter stations (at least one per system) to limit the voltage in the event of an overvoltage in the DC system. The DC chopper is modelled separately and independently from the AC/DC converter. Two models are available:
    - Highly simplified model - consisting of one or two DC voltage sources and one or two diodes.
    - Detailed model - consisting of one or two controlled resistors, one or two actively switched power electronic valves and the controller.
- DC nodes or DC busbars
- DC lines/cables
- Choke coils
  - Placed at the ends of the DC lines/cables to influence the current/voltage gradients.
- DC circuit breakers
  - Placed on the DC terminals of the AC/DC converters or the ends of the lines/cables in the DC grid.

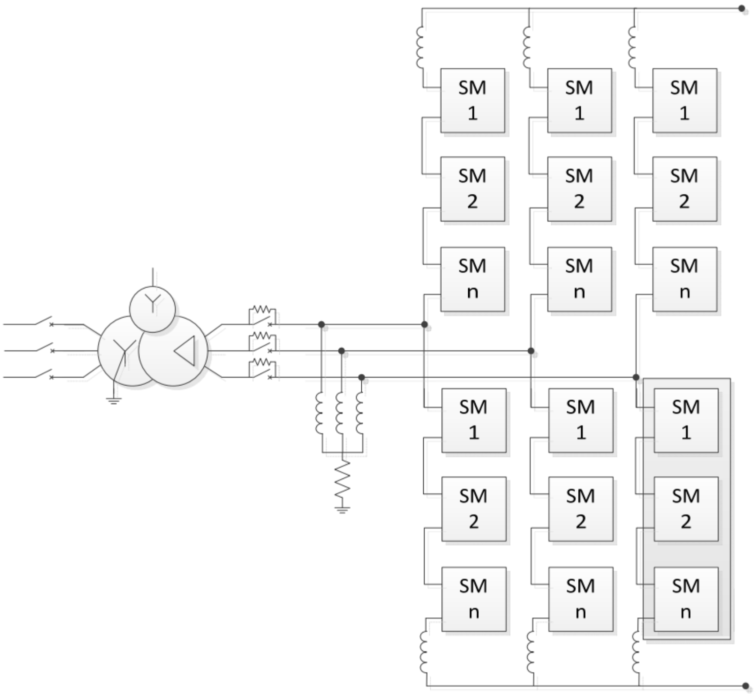

FIGURE 5.3 MODULAR MULTILEVEL CONVERTER TOPOLOGY [6]

The RMS/EMT part of the model contains a collection of dynamic models which simulate the control and protection functions of HVDC systems and converter stations in the RMS and EMT domains. The initialization of dynamic models is done automatically based on the solution of the load flow calculation and with the help of initialization equations additionally stored in the dynamic models. The interconnection of the dynamic control models is given in Figure 5.4, where each slot represents a different control system.

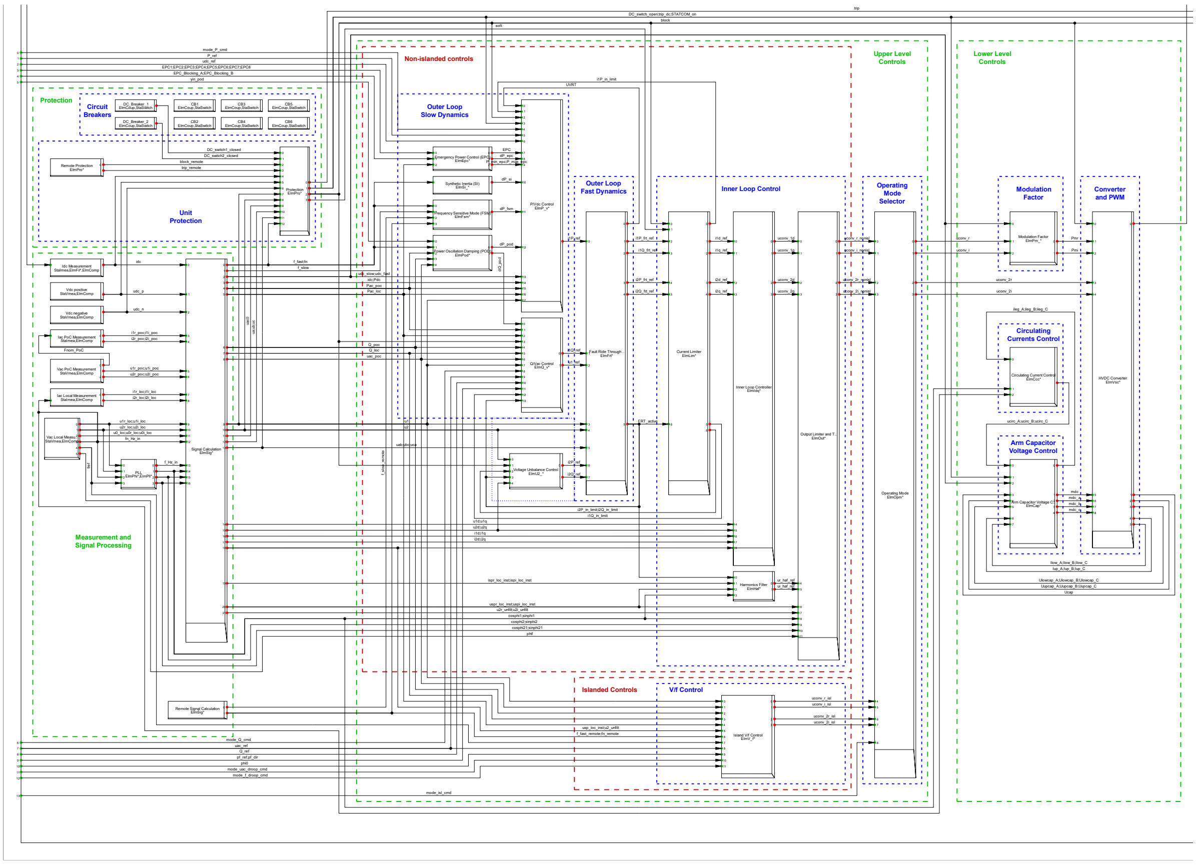

FIGURE 5.4 HVDC CONTROL SYSTEM DIAGRAM

The measuring points for the input signals of the control and protection functions of the converter station are marked in Figure 5.5. The selection of used measurements depends on the type of HVDC system (onshore / offshore) and the selected parameterization.

Transformation of signals from the stationary coordinate system (*abc* reference frame - alpha beta components) into rotating coordinate system *(dq* reference frame - *dq* components) is done with Clarke-Park transformation inside the Signal Calculation block.

The inverse signal transformation (from the rotating coordinate system into the stationary coordinate system) is done by inverse Park transformation inside the Output Limiter and Transformation block.

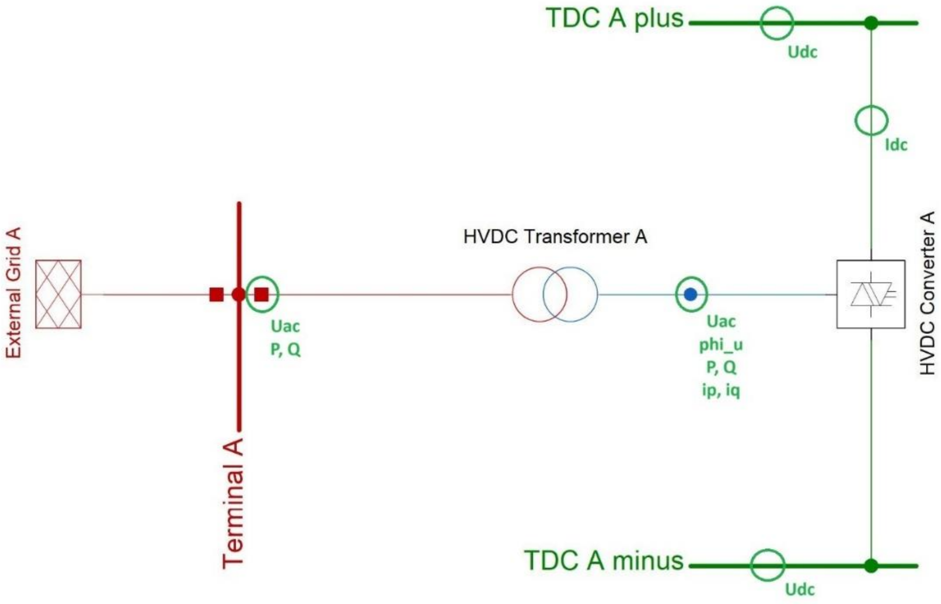

FIGURE 5.5 MEASURING POINTS FOR THE INPUT SIGNALS OF THE CONTROL AND PROTECTION FUNCTIONS OF A CONVERTER STATION

5.3.4 Model exchange

The static parts of the MMC model that are listed in the previous section, can be mapped to various subclasses of the *DCConductingEquipment* class in CIM, e.g. HVDC converter to *ACDCConverter* class, HVDC transformer to *PowerTransformer*, DC chopper to *DCChopper*, DC nodes or DC busbars to *DCNode* and *DCTerminal*, DC lines/cables to *DCLineSegment,* Choke coils to *DCSeriesDevice*, and DC circuit breakers to subclasses of *DCSwitch,* respectively. None of the abovementioned classes required extensions to CIM due to the static part being adequately covered in the latest CIM version.

The dynamic model is serialized in CIM XML files using *DetailedModelConfigurationProfile* (DMC) of IEC 61970-457:2024 [7], as well as Modelica code.

The CIM model includes classes needed to exchange the dynamic model configuration, i.e. the structure and connectivity of a detailed model, whereas the Modelica model includes equations which explicitly describe the model dynamics. The blocks of the CIM HVDC MMC control model are represented by separate DMC instances and given in Table 5.3.

TABLE 5.3: TTG HVDC RMS/EMT MODEL BLOCKS

BLOCK	MODEL NAME	DESCRIPTION
HVDC Converter	-------	HVDC converter (primary technology)
Operating Mode	opm_Operating Mode	Selection for using the control output signals for mains parallel operation or isolated operation
Island V/f Control	V_f Control	Regulation of voltage level and frequency

P/Vdc Control	P_Vdc Control	Control of active power (on the AC or DC side) or voltage on the DC side
Q/Vac Control	Q_Vac Control Flexible Output	Reactive power control (on the AC side) or voltage magnitude on the AC side
Emergency Power Control (EPC)	EPC TenneT	Emergency Power Control (EPC) according to TenneT specification
Frequency Sensitive Mode (FSM)	fsm_Freq Sensitive Mode TenneT	Generates setpoint changes of the active power in frequency dependency
Power Oscillation Damping (POD)	pod_Power Oscillation Damping	Generates setpoint changes of the active or reactive power depending on an input variable
Synthetic Inertia (SI)	si_Synthetic Inertia	Generates setpoint changes of the active power depending on the frequency (or the frequency derivative) with the aim of emulating mechanical inertia
Voltage Unbalance Control	u2_Voltage Unbalance Control	Regulation to reduce voltage asymmetries (negative sequence voltage) in normal operation
Harmonics Filter	haf_Active Harmonics Filter	Active harmonic filter
Fault Ride Through (FRT)	FRT Control or Continuous Vac Ctrl	Dynamic support: additional reactive current depending on the over- or undervoltage or continuous voltage regulation with proportional controller (fast outer control loop)
Current Limiter	Limiter Current	Current limitation for mains parallel operation
Inner Loop Controller	idq_Current Control	Internal control for mains parallel operation (usually current control, alternatively voltage regulation)
Output Limiter and Transformation	Output Limiter Transform	Output voltage limitation and inverse transformation of the signals
Modulation Factor	pm_Modulation Factor	Conversion of the voltage output signal of the controller into the modulation factor (considering the HB-MMC or FB-MMC technology)
Arm Capacitor Voltage Control	cap_MMC Capacitor Control	Regulation of the voltage of the arm capacitors (considering the aggregate arm model or simplified controller structure)
Circulating Current Control	ccc_Circulating Current Control	Regulation for suppressing circulating currents in the MMC
Signal Calculation	Signal Calculation	Processing of the measured variables (coordinate transformation, filtering) and calculation of the input signals for the control
PLL	PLL DDSRF Nested Neg. Seq. PLL	Phase-Locked Loop (PLL) for synchronization to the voltage angle and frequency measurement
Remote Signal Calculation	Signal Calculation	Preparation of the measured quantities and calculation of the input signals for the control of the remote end of the HVDC system
Protection	Protection ACDC	Self-protection and decoupling protection of the HVDC converter or HVDC system
Remote Protection	Protection ACDC	Self-protection and decoupling protection of the HVDC converter at the remote end of the HVDC system

The frames for signal measurement are summarized in Table 5.4.

TABLE 5.4: TTG HVDC RMS/EMT MODEL FRAMES

FRAME	MODEL NAME	DESCRIPTION
Vdc positive	Frame Voltage Measurement DC	Measurement of the positive DC voltage
Vdc negative	Frame Voltage Measurement DC	Measurement of the negative DC voltage
Idc Measurement	Filter idc	Measurement of the DC current
Vac Local Measurement	Frame Voltage Measurement AC	Measurement of the AC voltage at the local AC terminal of the HVDC converter
Iac Local Measurement	Frame Current Measurement AC	Measurement of the AC current at the local AC terminal of the HVDC converter
Vac PoC Measurement	Frame Voltage Measurement AC	Measurement of the AC voltage at the grid connection point of the HVDC converter
Iac PoC Measurement	Frame Current Measurement AC	Measurement of the AC current at the grid connection point of the HVDC converter

5.4 Voltage source converter

5.4.1 Context

The model was created to analyse the impact of VSC-HVDC transmission systems on various power system stability aspects such as voltage and rotor angle stability. As part of this goal, a main aspect was to derive a generic vendor independent VSC-HVDC model that could be used in the early stages of the network planning process where only limited information about the exact configurations is given [12].

5.4.2 Model use, assumptions, validity domain and limitations

The model is part of an average value system model (RMS) and is therefore based on the same assumptions that RMS-modelling entails. Thus, it has a very limited frequency range centred around 50 Hz. The high frequency aspects of the VSC are neglected. Furthermore, the DC quantities, due to their fast dynamics, are seen as instantaneous values within the model. Through the linkage of the AC side voltage to the DC side, the model is independent of the actual converter topology (multilevel, cascaded…) and the DC network topology (monopole/bipole). In addition, by neglecting conversion losses and filters the model is further generalized. The main purpose of the model is therefore not to depict functionalities of the VSC into detail but focus more on the VSC in the context of grid analysis of large grid excerpts. It can be used within the network planning process where several grid expansion states need to be analysed for different stability aspects. Where the grid excerpt of interest is large, and the focus is mainly on large signal disturbances as for example system splits. It is not necessarily suitable for detailed analysis of fast converter dynamics or interaction between converters [12].

5.4.3 Model description

The complete VSC model includes in addition to the VSC core part an outer- and inner control model as well as a PLL component. The equations and implementations are stated in the following sub-sections. A table with the parameter and variable definitions is given at the end of each sub-section.

About the notation in general: a lowercase letter indicates that the value of the variable is given in p.u. and a “*” indicates reference values. A “ ‾ ” indicates that it is a limited variable. Complex variables are indicated by a “_”. The initialization values of the state variables are given when the variable is first mentioned. For all other variables, the initial values can be derived from the initial load flow. The calculations take place in the p.u. system.

PLL:

PLL block diagram is shown in Figure 5.6.

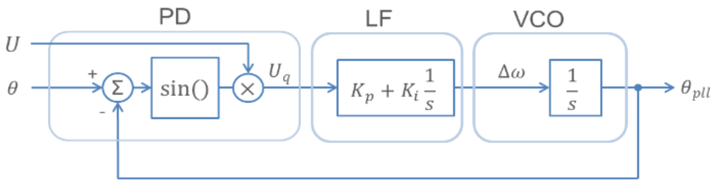

FIGURE 5.6 PLL BLOCK DIAGRAM

Inputs, outputs, parameters, state variables and equations are presented below.

Input: U , $\theta, \theta_{pll}, x_{pll}$

Output: U_d , U_q , θ_{pll}

Parameters: $K_i,\ K_p$

State Variables: θ_{pll}, x_{pll} with $\theta_{pll,0} = \theta_{SS}\ and\ x_{pll,0} = 0$

Equations:

$$U_d = \mathrm{U} * \cos(\theta - \theta_{pll})$$

$$U_q = \mathrm{U} * sin(\theta - \theta_{pll})$$

$\Delta\omega_{PLL} = K_p * U_q + K_i * x_{PLL}$

$$\frac{d\theta_{pll}}{dt} = \Delta\omega_{PLL}$$

PLL parameters and variables are described in Table 5.5.

TABLE 5.5: PLL PARAMETERS AND VARIABLES DESCRIPTION

PARAMETER	**DESCRIPTION**
K_i	PLL loop filter integral gain
K_p	PLL loop filter proportional gain
Algebraic Variables	**Description**
U	AC bus voltage magnitude
θ	AC bus voltage angle
U_d	AC bus voltage d component
U_q	AC bus voltage q component
$\Delta\omega_{PLL}$	PLL speed change
State Variables	**Description**
θ_{pll}	PLL angle
x_{PLL}	PLL loop filter integrator

Outer-Control:

Depending on which variables should be controlled (X_d and X_q) there are 4 operation modes. The modes only differ in their input variables. Inputs, outputs, parameters, state variables and equations are presented below.

Input:

1. P^*, P , U_{ac}^*, U_{ac} (Active power control and AC voltage regulation)
2. U_{dc}^*, U_{dc}, U_{ac}^*, U_{ac} (DC and AC voltage regulation)
3. P^*, P , Q^*, Q (Active and reactive power control)
4. U_{dc}^*, U_{dc}, Q^*, Q (DC voltage regulation and reactive power control)

Output: $I_{d,Out}^*$, $I_{q,Out}^*$
Parameters: $K_{i,d}$, $K_{i,q}$, $K_{p,d}$, $K_{p,q}$, K_{awd}, K_{awq}
State Variables: N_d, N_q with $N_d = 0$ and $N_q = 0$
Equations:

$$I_{d,Out}^* = K_{p,d} * (X_d^* - X_d) + K_{i,d} * N_d + I$$

$$N_d = \int dN_d$$

$$dN_d = (X_d^* - X_d) + K_{awd} * (I_{d,Out}^* - I_d^*)$$

$$I_{q,Out}^* = K_{p,q} * \left(X_q^* - X_q\right) + K_{i,q} * N_q + I$$

$$N_q = \int dN_q$$

$$dN_q = \left(X_q^* - X_q\right) + K_{awq} * (i_{q,Out}^* - i_q^*)$$

Current Limiter

Outer Control Loop with Current Limiter is shown in Figure 5.7.

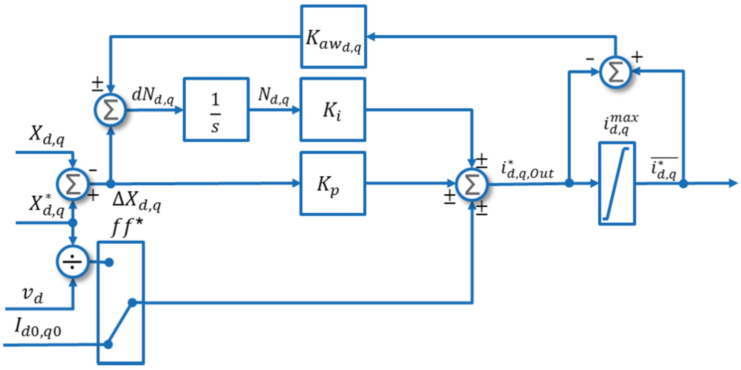

FIGURE 5.7 OUTER CONTROL LOOP WITH CURRENT LIMITER

Inputs, outputs, parameters, state variables and equations are presented below.

Input: $I_{d,Out}^*$, $I_{q,Out}^*$
Output: $\overline{I_d^*}$, $\overline{I_q^*}$
Parameters: $I_{max,d}$, $I_{max,q}$
Equations:

$$-I_{max,d} \leq I_d^* \leq I_{max,d}$$

$$-I_{max,q} \leq I_q^* \leq I_{max,q}$$

Outer control loop and current limiter parameters and variables are described in Table 5.6.

TABLE 5.6: OUTER CONTROL AND CURRENT LIMITER PARAMETERS AND VARIABLES DESCRIPTION

PARAMETERS	**DESCRIPTION**
$K_{i,Xd}$	Integral gain of PI Controller for d component
$K_{i,Xq}$	Integral gain of PI Controller for q component
$K_{p,Xd}$	Proportional gain of PI Controller for d component
$K_{p,Xq}$	Proportional gain of PI Controller for q component
K_{awd}	Anti windup coefficient for d component
K_{awq}	Anti windup coefficient for q component
$I_{max,d}$	Maximum d component current reference
$I_{max,q}$	Maximum q component current reference
Algebraic Variables	**Description**
N_d	Integrator in d axis controller
N_q	Integrator in q axis controller
P^*	Active power reference
Q^*	Reactive power reference
U_{ac}^*	DC voltage reference
U_{dc}^*	AC voltage reference
$I_{d,Out'}^*$	d component current reference (unlimited)
$I_{q,Out'}^*$	q component current reference (unlimited)
$\bar{I}_d^{*,}$	d component current reference (limited)
$\bar{I}_q^*$	q component current reference (limited)
dN_d	Integral control deviation d axis
dN_q	Integral control deviation q axis
State Variables	**Description**
N_d	Integrator in d axis controller
N_q	Integrator in q axis controller

<u>Inner-Control:</u>

Inputs, outputs, parameters, state variables and equations are presented below.

Input: $U_d, U_q, I_d, I_q, E_{d0},\ E_{q0}$
Output: $E_d^{*,}\ ,\ E_q^*$
Parameters: $K_{p,d},\ K_{p,q},\ K_{i,d},\ K_{i,q}, X_{pr}$
State Variables: $M_d,\ M_q$ with $M_{d,0} = 0\ M_{q,0} = 0$
Equations:

$$\dot{M}_d = \Delta I_d = I_d^* - I_d$$
$$\dot{M}_q = \Delta I_q = I_q^* - I_q$$
$$M_d = \int \dot{M}_d$$
$$M_q = \int \dot{M}_q$$
$$E_{d,}^* = K_{p,d} * \Delta I_d + K_{i,d} * M_d + E_{d0} - I_q * X_{pr} + U_d$$
$$E_q^* = K_{p,q} * \Delta I_q + K_{i,q} * M_q + E_{q0} + I_d * X_{pr} + U_q$$

<u>Limiter:</u>
Input: $U_{dc},\ E_d^*,\ E_q^*$

Output: $\bar{E}_d^*,\ \bar{E}_q^*$
Parameters: M_{max}
Equations:

$$\underline{E}^* = E_d^* + j * \ E_q^*$$

$$\bar{E}_d^* = E_d^* * \frac{\max\left(\left|\underline{E}^*\right|, M_{max} * U_{dc}\right)}{\left|\underline{E}^*\right|}$$

$$\bar{E}_q^* = E_q^* * \frac{\max\left(\left|\underline{E}^*\right|, M_{max} * U_{dc}\right)}{\left|\underline{E}^*\right|}$$

Inner control and limiter parameters and variables are described in Table 5.7.

TABLE 5.7: INNER CONTROL AND LIMITER PARAMETERS AND VARIABLES DESCRIPTION

PARAMETERS	**DESCRIPTION**
$K_{i,d}, K_{i,q}$	Integral gain for the PI Controller d/q-component
$K_{p,d}, K_{p,q}$	Proportional gain for the PI Controller d/q-component
X_{pr}	Phase reactance
M_{max}	Maximum modulation index
Algebraic Variables	**Description**
E_{d0}	Steady State voltage drop d component
E_{q0}	Steady State voltage drop q component
$E_d^{*,}$	d component valve voltage reference (unlimited)
$E_q^{*,}$	q component valve voltage reference (unlimited)
U_{dc}	**DC voltage**
$\bar{E}_d^*$	d component valve voltage reference (limited)
$\bar{E}_q^*$	q component valve voltage reference (limited)
State Variables	**Description**
M_d	Integrator in the PI Controller
M_q	Integrator in the PI Controller

<u>Simplified Valve Control:</u>
Inputs, outputs, parameters, state variables and equations are presented below.

Input: $\bar{E}_d^*, \bar{E}_q^*, U_{dc}$
Output: $E_q,\ E_d$
Parameters: $T_a, k_{Udc}, R_{pr}, X_{pr}$
State Variables: E_d, E_q with $E_{d,0} = R_{pr} * I_{d,0} - X_{pr} * I_{q,0} + U_0 - U_{dc,0} * k_{Udc}$

$$E_{q,0} = R_{pr} * I_{q,0} + X_{pr} * I_{d,0} + 0 - U_{dc,0} * k_{Udc}$$

Equations:

$$\frac{dE_d}{dt} = \frac{1}{T_a} * (\bar{E}_d^* - (E_d + U_{dc} * k_{Udc}))$$
$$\frac{dE_q}{dt} = \frac{1}{T_a} * (\bar{E}_q^* - (E_q + U_{dc} * k_{Udc}))$$

Valve control parameters and variables are described in Table 5.8.

TABLE 5.8: VALVE CONTROL PARAMETERS AND VARIABLES DESCRIPTION

PARAMETERS	**DESCRIPTION**
T_a	1st order time lag valve control approximation
k_{Udc}	DC voltage dependency on U
X_{pr}	Phase reactance
R_{pr}	Phase resistance
Algebraic Variables	**Description**
$\bar{E}_d^*$	d component valve voltage reference (limited)
$\bar{E}_q^*$	q component valve voltage reference (limited)
U_{dc}	DC voltage
State Variables	**Description**
E_d	d component modulated valve voltage
E_q	q component modulated valve voltage

VSC Model:

VSC model is shown in Figure 5.8.

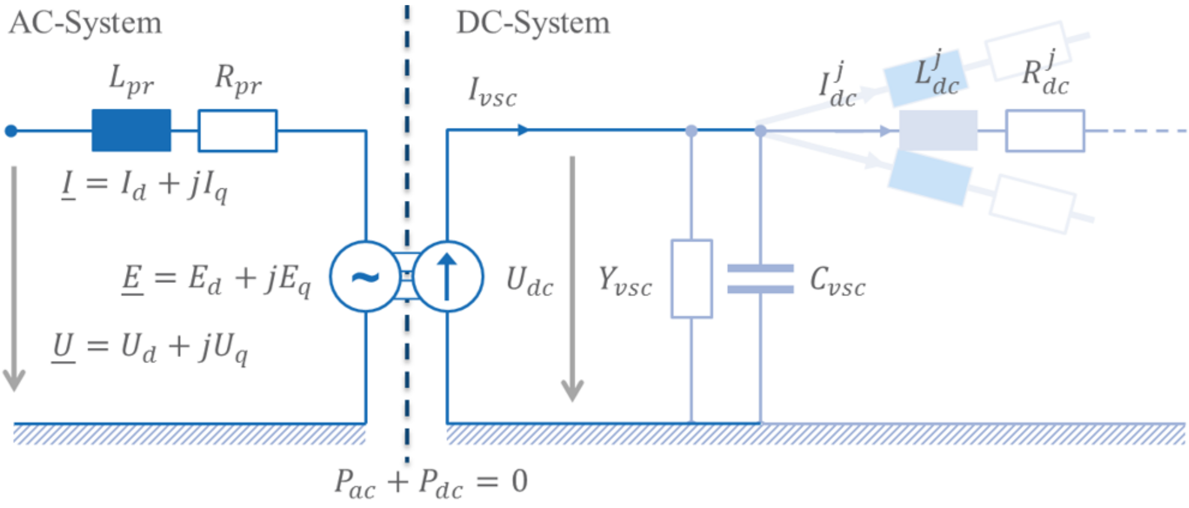

FIGURE 5.8 VSC MODEL

Inputs, outputs, parameters, state variables and equations are presented below.

Input: E_d,E_q, U_d , U_q , θ_{pll}, U_{dc}

Output: I_r, I_i, I_{VSC}

Parameters: R_{pr}, X_{pr}, k_{Udc}

State Variables: E_d,E_q, θ_{pll}, I_q, I_d with $I_r = Re\{\frac{P_0}{U_0}\}$ and $I_i = -Im\{\frac{Q_0}{U_0}\}$

Equations:

$$L_{pr} * \frac{di_d}{dt} = -R_{pr} * I_d + X_{pr} * I_q + E_d + U_{dc} * k_{Udc} - U_d$$

$$L_{pr} * \frac{di_q}{dt} = -R_{pr} * I_q + X_{pr} * I_d + E_q + U_{dc} * k_{Udc} - U_q$$

$$P_{ac} = U_d * I_d + U_q * I_q$$

$$P_{dc} = -(E_d * I_d + E_q * I_q) * k_{Udc} * U_{dc}$$

$$I_{vsc} = \frac{P_{dc}}{U_{dc}}$$

$$I_r = \cos(\theta_{pll}) * I_d - \sin(\theta_{pll}) * I_q$$

$$I_i = sin(\theta_{pll}) * I_d + \cos(\theta_{pll}) * I_q$$

VSC model parameters and variables are described in Table 5.9.

TABLE 5.9: VSC MODEL PARAMETERS AND VARIABLES DESCRIPTION

PARAMETER	DESCRIPTION
k_{Udc}	DC voltage dependency on U
X_{pr}	Phase reactance
R_{pr}	Phase resistance
Algebraic Variables	**Description**
I_r	Real current fed into AC system
I_i	Imaginary current fed into AC system
I_{VSC}	Current injected into DC system
U_{dc}	DC voltage
U_d	AC bus voltage d component
U_q	AC bus voltage q component
State Variables	**Description**
E_d	d component modulated valve voltage
E_q	q component modulated valve voltage
I_d	d component current through AC phase reactor
I_q	q component current through AC phase reactor
θ_{pll}	PLL angle

5.4.4 Model exchange

The static part of the voltage source converter model includes the electrical circuit, that can be mapped to existing *Equipment* classes in canonical CIM without a need for extension. The dynamic part of the voltage source converter model includes the control system, the equations are provided in MATLAB code. The intended approach to exchange the dynamic part of the model is to serialize it to CIM XML using the *DetailedModelConfigurationProfile* of IEC 61970-457:2024 [7], that allows to include MATLAB or Modelica code into <cim:FunctionDescriptor.equation>.

6 Conclusion

HVDC-Wise lib provides an open-source, standardized platform for the exchange of HVDC equipment models, advancing efforts in the energy industry to adopt HVDC technology on a broader scale. By dividing the models into static and dynamic parts, the library ensures that essential data and mathematical models can be easily exchanged and implemented in various tools, contributing to long-term interoperability.

The developed models demonstrate that the workflow proposed in [2] can be implemented with different variants for the dynamic part, including Modelica equations, MATLAB equations and FMU. It also allowed to show that actual standards are sufficient to develop some models whereas some extensions are needed for others. This report is mainly a description of the library itself, more information on the approach used to build the models, identified gaps and lessons learned are available in [2] and further recommendations will be proposed in deliverable D8.3 of the project.

This library is positioned as a critical resource for users interested in integrating HVDC models into their environments, as well as for stakeholders working toward the standardization of HVDC models at a national or international level. As **HVDC-Wise lib** evolves, it will continue to support the IEC CIM standards and promote the seamless exchange of dynamic modelling data, driving innovation in the field of HVDC technology. Mature models could be integrated into the CRESYM collaborative open-source library[6] (COLib). The structure of **HVDC-Wise lib** model documentation is based on the CoLib documentation template, which ensures a simpler integration of **HVDC-Wise lib** models to CoLib.

By fostering collaboration, encouraging contributions from the community, and supporting international standardization efforts, the **HVDC-Wise lib** is well-positioned to become a foundational tool in the development and deployment of HVDC technology globally.

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