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# Standardized Model Exchange of HVDC Equipment for RMS and EMT Simulations

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**Abstract**—IEC Common Information Model (CIM) standards including IEC Common Grid Model Exchange Standard (CGMES) are used by Transmission System Operators (TSOs) for AC power system models exchange in long-term and operational planning processes. Exchange of HVDC models is an essential component to model power system behaviour. IEC standards support essential minimum, but extensions are necessary due to additional requirements for HVDC systems and their controls. This paper provides an insight into the research activities held in the HVDC-WISE project towards creation of a public library of models of HVDC equipment, based on IEC CIM standards. This paper highlights the goals and demonstrates the proposed approach for representing the static and dynamic parts of the models. It also addresses the challenges and discusses the current status of the work.

**Index Terms**—HVDC systems, model exchange, CIM, CGMES, Modelica, FMI.

## I. INTRODUCTION

Power system development and operational planning are complex cross-organizational business processes. Requirements of these business processes are defined in the European legislation, e.g. the European regulations such as EU Regulation 2017/1485 on establishing a guideline for electricity transmission system operation and EU Regulation 2022/869 on guidelines for trans-European energy infrastructure. These processes cannot be executed if there is no exchange of models representing all necessary details of both AC and DC parts of the European power system. This includes offshore interconnections and multiterminal HVDC architectures commissioned or planned in Europe. As illustrated in Fig. 1, the model exchange involves various power system modelling and simulation tools utilized by Transmission System Operators (TSOs) for power flow calculations (static analyses), root mean square (RMS), electromagnetic transient (EMT) and dynamic phasor (DP) simulation (so far predominantly, static and RMS). The exchanged models need to be interoperable

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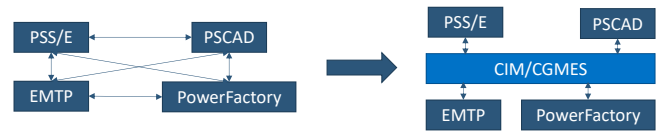


Fig. 1: Illustration of need for standard-based model exchange

because, in a single business process, there are over 50 entities involved, each using different tools for various studies.

To cope with the interoperability challenge and satisfy requirements for model exchange, a common information model is necessary as a minimum requirement. The IEC published a set of standards that defined the Common Information Model (CIM) and the Common Grid Model Exchange Standard (CGMES, IEC 61970-600-1:2021, IEC 61970-600-2:2021). This family of standards together with IEC CIM for Dynamics standard (IEC 61970-457:2024) provides a solid basis for meeting requirements of power system model data exchange. These standards have been used quite extensively by TSOs and some Distribution System Operators (DSOs) to exchange AC power system model data in system development and operational planning.

As discussed in [1], model exchange in modern hybrid AC/DC power systems poses new requirements for IEC CIM-related standards, namely:

- 1) Support model exchange of both open-source and black box (compiled) models representing equipment and its controls’ behaviour.
- 2) Support model exchange of HVDC equipment, including complex configurations and details necessary for modelling of equipment for static (power flow) calculation.
- 3) Support cross-domain model exchange, e.g., a model from RMS tool to be exchanged with EMT tool.

Along with these requirements, the following use cases are identified as key to enable seamless interactions between entities in the exchange and to be able to cope with confidentiality and intellectual property (IP) rights to which model exchanges need to adhere to:

- An exchange of black box, where the details are part of a compiled model.
- An exchange of open-source model where equations describing the model are defined by code (e.g., in Modelica, Matlab languages or regular mathematical expressions) and the code is referenced.
- An exchange of open-source model where equations are defined and are explicitly exchanged as part of the data exchange.

There are numerous variants of these use cases, as there are different ways of defining equations, e.g., by regular mathematical expressions. There are also different ways to exchange the compiled code, e.g., by referencing a .dll or other compiled code. These use cases can be applied to the dynamic part of the RMS model or to EMT models.

The new edition of IEC 61970-457 standard tackles the first requirement, i.e. to support exchanges based on open source and black box models. This is done by using Detailed Model Configuration profile, allowing to model dynamic equations with Modelica, Matlab or regular mathematical expressions. To meet the second requirement mentioned above, there is a need to build up the knowledge about which DC equipment models are crucial for model exchange, how they can be modelled with CIM. The HVDC-WISE project aims at leveraging the full potential of HVDC to enhance the resilience and reliability of hybrid AC/DC transmission systems through effective planning and operation. It brings together industry and academia to create (among other deliverables) a public library of HVDC-related models. This library, named hereunder “HVDC-WISE Lib”, is based on IEC CIM and hosts models of AC/DC power system equipment and control features. The goals of the HVDC-WISE lib are twofold. Firstly, the library provides guidance on how it can be further populated, e.g., how models can be converted to required format. This includes discussion about how the library will be maintained as an open-source resource. Secondly, HVDC-WISE lib aims to support standardization of hybrid AC/DC equipment models exchange, so that different power system simulation tools can handle the interface and perform simulations.

To successfully standardize control dynamic models for devices, it is crucial to take a comprehensive approach that ensures these models accurately reflect real-world performance. However, when dealing with studies looking at assessing new designs and integrating new technologies, the real-world performance is unknown. Invaluable insights into actual device performance and expected behaviour of models and design concepts can be gained by consulting TSOs and vendors from the outset. Such collaborative effort would help create standardized models that not only adhere to theoretical specifications but also encompass all relevant existing or expected behaviours and capabilities with high accuracy thus avoiding creating overly hypothetical models that may not align with practical implementations. HVDC-WISE Lib helps the community by exposing available models described in a standardised data exchange form which enables TSOs and other entities to perform simulation in their planning stud-

ies along with any harmonisation efforts and standardisation activities to fine tune the details of the models. This should be seen as a step-wise approach where available models are used and maintained by the community.

During the initial analyses, the authors investigated various data exchange options and concluded on the set of approaches presented in the methodology section of this paper. The workflow on how to bring a model to HVDC-WISE Lib is explained in detail in section II. Section III presents the application of the methodology, including the example of a DC energy storage model. It also discusses the challenges and lessons learned from this process. Finally, Section IV describes a set of proposals that should be addressed to IEC to cover identified gaps in published standards and section V provides a conclusion and perspectives related to this work.

## II. METHODOLOGY

The following approach has been initially selected for description of models in HVDC-WISE Lib. Static parts of the HVDC equipment (i.e., electrical circuits of the equipment) are modelled by extending the canonical CIM and related data exchange profiles to include new classes, relationships and attributes. Dynamic parts of HVDC equipment (i.e., control logic of the equipment) are modelled with Modelica code using Detailed Model Configuration profile. In this approach, the dynamic model equations are treated as instance data and do not require extension of the IEC CIM standards. The data flow diagram in Fig. 2 illustrates the workflow to bring a model to HVDC-WISE Lib. The workflow slightly alters from initially selected approach and includes learnings from the work on bringing pilot models to the library. The workflow is discussed in detail in the following.

### A. Identification of Static and Dynamic Parts

As a starting point, a project partner provides a model for identification of static and dynamic parts. Providing a model implies providing the full model documentation, along with demonstrating the implementation in the software.

Splitting the model into static and dynamic parts is most natural and intuitive for the purpose of model exchange and not necessarily reflect the way how the model is run in a simulation. The RMS and EMT simulation approach differs in terms of how electrical grid is described. RMS uses complex algebraic equations and EMT differential equations to model electrical grids (cables, overhead lines, transformers and their connectivity). In EMT, the split between static part and dynamic part might not be that obvious and this should not be confused with the approach taken on model exchange side. Therefore, the main consideration for separation of the model into static and dynamic parts is what needs to be exchanged. For static part of the model, the data are exchanged, e.g., model topology and equipment parameters. For dynamic part of model, the actual model equations and optionally even the solver are exchanged.

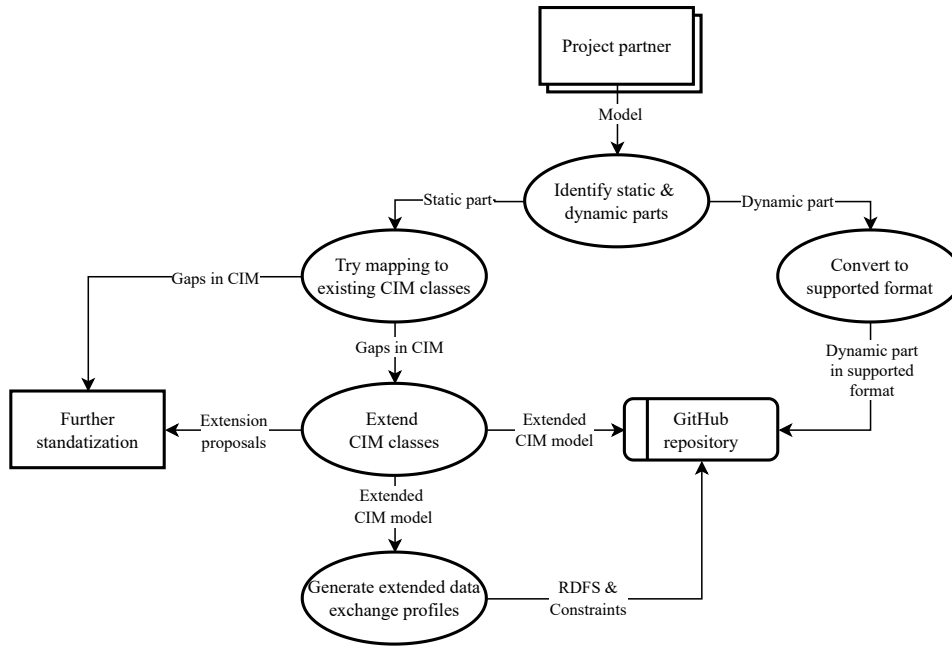


Fig. 2: Workflow to bring a model to HVDC-WISE Lib

### B. Static Part

After splitting a model into static and dynamic parts, the next step for the static part is to try describing it with existing classes, attributes and relationships in the latest released version of IEC CIM standards. As so far IEC CIM standards have been mostly geared towards AC grid data exchange, mapping of DC equipment is not always possible. In this case, the gaps in CIM for exchange of DC equipment are identified and provided as an input for CIM extension in the HVDC-WISE project and for further recommendations for IEC CIM standardization.

Normally, the extension of CIM involves adding new classes, attributes, and relationships that are not present in the standard but are necessary to describe the static part. These changes are added to the canonical data model describing the CIM and later on profiled for the purpose of a structured data exchange based on RDF framework [2] (a Resource Description Framework standardised by W3C) that requires generation of an RDF Schema file to describe the data exchange profile. A custom “HVDCwise” namespace is used to differentiate the extended elements from the standard CIM elements. The extended CIM data model is stored in a GitHub repository, hosting HVDC-WISE Lib.

The end effect is that the data exchange standards (e.g. CGMES or Dynamics profile) are covering additional equipment and its controls. This would eventually result in a new release of the standard that includes classes, attributes and relationships from the extended data model.

### C. Dynamic Part

The identified dynamic part of the equipment model needs to be converted to a serialisation format, supported by IEC CIM standards for dynamic model exchange. As mentioned earlier, the initially defined approach was to exchange dynamic part using Modelica equations in accordance with Detailed Model Configuration profile from the new edition of IEC 61970-457 standard.

Multiple project partners contribute to HVDC-WISE Lib and the models are originally available in different modelling and simulation tools. The resources to convert dynamic parts of the model to a particular form of equations can be time consuming, error-prone and would create a bottle neck for the project if the data exchange would support only one language for describing the models. HVDC-WISE partners welcomed the setup of the CIM for dynamics standards that have sufficient support for open-source code exchange and exchange of compiled models.

The dynamic model exchange formats, dealt with in the HVDC-WISE project, include exchange of:

- Modelica equations in accordance with Detailed Model Configuration profile.
  - Matlab equations in accordance with Detailed Model Configuration profile.
  - Compiled models in accordance with FMI standard [3].
- In this case, compiled model is exchanged as an artifact.

The dynamic part is converted to one of these formats and stored in a GitHub repository, hosting HVDC-WISE Lib.

TABLE I: Initial set of models for HVDC-WISE Lib

Name	Description	Project partner	Domain
HVDC MMC	Model includes control modules: synthetic inertia, frequency sensitive mode, power oscillation damping, P/Vdc control, Q/Vac control, voltage unbalance control, fault ride through.	TenneT	RMS
DC energy storage	Model of a chain link of energy storage submodules, see section III.B and [4].	Supergrid Institute	EMT
Voltage source converter	Generic voltage source converter HVDC model for power system stability studies, described in [5].	RWTH	RMS
Grid-following inverter	Average value inverter model with grid-following control, described in [6].	RWTH	EMT

### III. APPLICATION

This section describes the application of the workflow to pilot models and reports some lessons learned.

#### A. Initial Set of Models

Table I presents models that are considered as part of the initial release of the HVDC-WISE Lib. The list of models is indicative, as there is continuous request to add additional models to the library. Some insights on the ‘‘DC Energy storage’’ are given below.

#### B. DC Energy Storage

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. The converter presented in [4] has been selected among the candidate technologies listed in section 2.5.2 of [7].

As shown in Fig. 3, it 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 each submodule capacitor.

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 in Fig. 4. 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

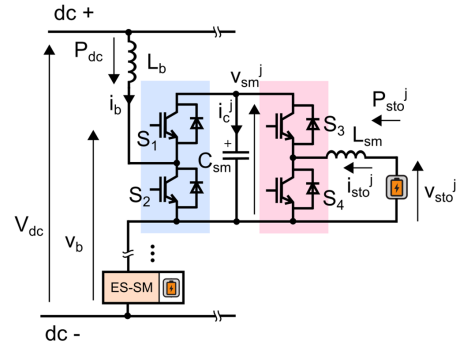


Fig. 3: Scheme of the considered DC energy storage

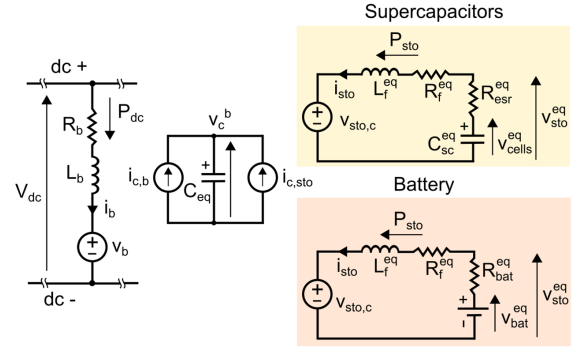


Fig. 4: Average model of the ES-SM branch considering supercapacitors or batteries as storage element

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.

For the model implementation, it has been decided to include in the static part only the elements connected to the DC terminals in Fig. 4: 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.

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 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

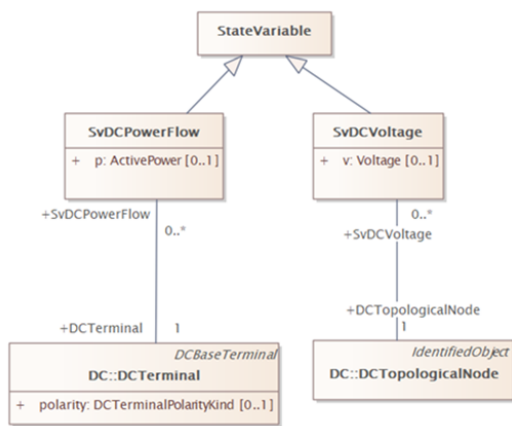


Fig. 5: Extensions regarding DC state variables

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. Creating this model also highlighted the limited capabilities for modelling of relationships between several dynamic modules. Extension of dynamic part to create a frame to describe relationship between different modules has also been proposed.

Dynamic part of the model includes the control of the converter. 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 [3].

#### IV. STANDARDIZATION RECOMMENDATIONS

The following proposals have been made during the piloting work on the HVDC-WISE Lib:

- Extensions to describe the static part of the DC storage model which includes the DC battery storage submodule and DC super capacitor storage submodule.
- A set of extensions to enable reporting on state variables for the DC part of the model i.e. to report power and voltage at the DC terminals and nodes. The polarity for the DC terminals was also added which is essential for modelling the VSC-based HVDC systems. Fig. 5 illustrates the proposed extensions that are prepared for inclusion in the next release of IEC CIM standards.
- An ability to explicitly describe a frame of the dynamic part of the model would facilitate modelling of the relationship between different modules of a control system.

As a consequence of the project, most of these extensions were discussed in the IEC and CIM open community and adopted for inclusion in the next release of the IEC CIM standards.

#### V. CONCLUSION

The methodology and analysis work presented in the paper gives confidence that a model exchange of HVDC systems

for performing complex studies is feasible. There are organizational, interoperability and standardization challenges to be addressed, but selecting the right direction enables work to be planned and performed for achieving the overall objectives. One of the key added values of the effort is to identify standardization gaps and propose CIM extensions in order to overcome the issues.

Models initially included in the HVDC-WISE Lib satisfy the outlined scope of the project and are valuable inputs for standardization work. They pave the way to share models for various studies and encourage the community to initiate collaborative projects and follow up on these activities. This stimulates proactive development of models required for simulation of complex scenarios in HVDC grids and enables equipment manufacturers to align with use cases and needs. It is well understood that not all models can be open source and not all models need to represent every detail of the equipment and its control. The IP rights concerns are taken care of by supporting exchange of black box models in addition to open source models. However, it also shall be recognised that open source models are needed to design the grid in a transparent way and perform wide area planning studies.

Once the HVDC-WISE Lib is initialised with a set of models, it is recommended to have an interoperability effort. This effort would involve testing of model import and cross-validation of simulation results with the models imported to different power system simulation tools. Any findings should lead to updating the versions of the models included in the library. This would enable TSOs and organisations like ENTSO-E to recognize the set of models in the library and recommend the usage in the planning or operational studies.

#### ACKNOWLEDGMENT

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