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European Network of
Transmission System Operators
for Electricity

ENTSO-E

CGM BUILDING PROCESS IMPLEMENTATION GUIDE

AC AND DC PART

FOR SYSTEM OPERATIONS

2.0 EDITION

25 AUGUST 2023

BUILDING PROCESS SUBTEAM (BP ST)

SOC APPROVED

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218 # REVISION HISTORY

Version	Release	Date	Comments
1	0	2022-12-06	Merge of AC and DC parts
1	0	2023-04-16	Changes applied due to 1) comments received from CGM BP ST, CGMES SG in the period 20 March 2023 – 14 Apr 2023. 2) Editorial and consistency related changes to improve readability of the document.
1	0	2023-04-28	Reviewed by CGM BP ST version. For OPDE TT approval.

NOTE CONCERNING WORDING USED IN THIS DOCUMENT

The force of the following words is modified by the requirement level of the document in which they are used.

MUST: This word, or the terms “REQUIRED” or “SHALL”, means that the definition is an absolute requirement of the specification.

MUST NOT: This phrase, or the phrase “SHALL NOT”, means that the definition is an absolute prohibition of the specification.

SHOULD: This word, or the adjective “RECOMMENDED”, means that there may exist valid reasons circumstances to ignore an item, but the full implications must be understood and carefully weighed before choosing a different course.

SHOULD NOT: This phrase, or the phrase “NOT RECOMMENDED”, means that there may exist circumstances when the particular behaviour is acceptable or even useful, but the full implications should be understood, and the case carefully weighed before implementing any behaviour described with this label.

MAY: This word, or the adjective “OPTIONAL”, means that an item is truly optional. One vendor may choose to include the item because a marketplace requires it or because the vendor feels that it enhances the product while another vendor may omit the same item. An implementation which does not include an OPTION MUST be prepared to interoperate with another implementation which does include the OPTION, though perhaps with reduced functionality. An implementation which does include an OPTION MUST be prepared to interoperate with another implementation which does not include the OPTION (except, of course, for the feature the option provides.)

DEPRECATED: this word means that a previously permitted entity should no longer be used in new implementations as in a future release the object in question may be suppressed.

1. Introduction

This implementation guide advises TSOs on the power system modelling necessary for the creation of Individual Grid Models (IGM), which is exchanged and used by the merging agent to perform the merging process, i.e., the merging of IGMs into a Common Grid Model (CGM). The merging process is performed repeatedly for different timeframes to serve the different RSC/RCC services that are using the CGM: Coordinated Capacity Calculation, Coordinated Security Analysis including regional services, Outage Planning and Short-Term Adequacy Forecast.

The CGM creation process has two-steps. In the first step TSOs, as a modelling authority, create power system models covering at least the network regions they are responsible of, and perform power flow calculations for it. This is a basis for the preparation of the IGMs. In the second step merging agents, e.g., Regional Security Coordinators – RSCs or RCC, collect and assemble IGMs into merged models – CGMs. As of Article 2(2) of Regulation (EU) 2015/1222 the term CGM refers to a Union-wide data set agreed between various TSOs describing the main characteristic of the power system (generation, loads and grid topology) and rules for changing these characteristics during the capacity calculation process. With the approval of other network codes and related methodologies the IGMs and CGMs are used not only for capacity calculation, but also in other business processes, as mentioned above. There can be similar models on the level of synchronous areas which strictly are no CGMs (not Union-wide) but merged models. In the document, whenever the term CGM is used it stands for both a CGM and a merged model except where the merged model is explicitly mentioned.

The CGM creation is envisaged as a fully automated process that does not require human attention if the power flow results satisfy the criteria stipulated for the business processes.

The exchange of IGMs and CGMs is based on the Common Grid Model Exchange Standard (CGMES). CGMES has different profiles that divide data in groups with different exchange cycles. This document focuses on the following profiles:

- Equipment (EQ) profile, an equipment instance file that describes the equipment of the power system model covered by a Modelling Authority Set. It is updated when the equipment changes. This data is referenced by instance data representing other profiles that are exchanged with higher frequency, e.g., every market time unit.
- Steady State Hypothesis (SSH) profile, a steady state hypothesis instance file that contains all objects required to exchange input parameters to be able to perform power flow simulations. It can be exchanged for every market time unit.
- Topology (TP) profile, a topology instance file that contains all topology objects for a Modelling Authority Set referencing the corresponding equipment and describing the output[1] of a topology processing of a model. It can be exchanged for every market time unit.
- State Variables (SV) profile, a state variable instance file that contains all objects required to exchange the result of a steady-state power flow solution. It can be exchanged for every market time unit.

Following currently established processes of IGM exchange over ENTSO-E operational planning data environment (OPDE) and the implemented solution, SSH, TP and SV profile must be exchanged for every market time unit.

[1] In CGMES v2.4 in the case where the connectivity is built based on TopologicalNode, the TP profile instance file can be considered as input.

A typical scenario of an exchange of a solved power system model of a TSOs would be to exchange one EQ instance file valid for several time stamps and one set of SSH, TP and SV instance files per time step, e.g., for every market time unit, depending on a time horizon. For example, in case of day-ahead congestion forecast process 24[2] sets are covering an energy delivery day but in case of intraday the data exchange can start up to 29[3] hours ahead, see also Table 3 and Table 4.

For a power flow calculation to create meaningful and reliable result, the exchanged data must meet quality criterions specified in detail in the CGMES [2] and QoCDC [3], i.e.

- The equipment data must be accurate and with good fidelity describe the real equipment. If this is not the case the power flow result may be meaningless.
- The market schedules must be mapped to power flow inputs close to loads and productions as they appear at injection points on the borders of the IGM. If this is not the case solved power flows and area interchanges may not be representative.
- Modelling of controls and constraints need to reflect real behaviour and limit values so power flow calculation response to contingencies is accurate.

The CGMES allows for detailed modelling of power systems, traditional bus branch style models as well as node breaker models including measurements. The detailed modelling enables better alignment between power flow results and the real state in the modelled power system. Latest versions of CGMES also allows detailed models to be combined with bus branch style models, which enables a gradual transition to more detailed modelling. The capability for detailed modelling also means more data to manage, keep consistent and of good quality.

This document replaces the CGM BUILDING PROCESS IMPLEMENTATION GUIDE AC PART (AC IG) version 1.3.

This version the CGM Implementation guide addresses the following topics:

a) HVDC modelling:

- Location of Shunts or filters used by current source converters.
- The HVDC boundary configuration to overcome the issue related to modelling of a BoundaryPoint in a Substation[4].
- The explicit modelling of HVDC links and poles that are not described in CGMES v2.4 or in CIM in general.
- Market schedule values linkage with HVDC poles to enable the poles split and loss calculation function (PSLC).
- Representation of HVDC links to properly respond to contingencies, remedial actions or changes in active power transfer when the response needs to be described so it can be simulated by the power flow algorithm.
- The usage of current source converter (CSC) filters which are primarily used for harmonics but can also be used for voltage control. Filters not used for harmonics are available for voltage control which requires a coordination of the filtering and voltage control

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[2] 23 (spring) and 25 (autumn) daylight saving.

[3] 30 in case of autumn daylight saving.

[4] Specification related definitions are included in Boundary and reference data exchange application specification.

functions.

- Guidance on how to model HVDC interconnections. As this is not a formal specification the restrictions and rules from this document will be defined in a next version of QoCDC or related specifications considering IEC 61970-600-1/2:2021, which was already updated regarding HVDC modelling.
- Improving readability of the document and its consistency with the present version of QoCDC. It also facilitates future transition of the contents in this document to next versions of CGMES. Therefore, the following should be noted:
- Annex A describes revisions of IEC 61970-301:2021, IEC TS 61970-600:2017 and IEC 61970-600:2021 documents.
- Annex C lists most of the HVDC revisions included in the IEC 61970-600:2021 compared to the IEC TS 61970-600:2017.
- Material from sections 11, 12 and 13 may be included in a coming version of IEC 61970-301, the IEC 61970-450 series profile specifications and IEC 61970-600.

2. Scope

This document contains information and restrictions about what data shall be included in AC IGM and a detailed HVDC model exported as a DC IGM that consists of CIMXML files. This document is based on CGMES v2.4 and provides some information in case there is different treatment in CGMES v3. On HVDC modelling, restrictions related to constraints and additional descriptions are derived based on a comparison done between IEC 61970-600:2021 and IEC TS 61970-600:2017, provided in Annex C. The QoCDC and related specifications will need revision to integrate relevant information from this document.

Multi terminal HVDC networks are outside the scope of this document. Only point to point HVDC Links are in scope. Any TSO with known future developments that might be multi terminal HVDC systems should use the simplistic method as an interim solution.

Equations that describe the converter are covered in the literature and IEC specifications. Detail modelling of the control functions of HVDC interconnection is not possible with CGMES v2.4 and it is considered out of the scope of this document. Contingencies and remedial actions changing the active power transfer over HVDC Poles are not covered as they are covered in ENTSO-E Network codes related profiles.

2.1 Concept of the document

This document contains not only guides for implementation but also other information that support implementation of the CGM building process.

In the future this document will be superseded by standards that cover the content in the different sections of the document. When this happens, this document will be modified to suit those standards, as complex processes always require guidelines.

2.2 Who should read what?

This document guides experts involved in the creation of IGMs as well as in various parts of the CGM building process. It is collecting extensive information about all cases, experiences, and relevant details gathered during a decade of implementation of the CGM process.

This section helps different readers to find the most relevant chapters based on their responsibilities. Experts reading this document should be familiar with CGMES and have access to referenced documents.

All readers should gain the basic understanding of the CGM building process based on the following chapters:

- 3 Related Documents
- 4 Definitions
- 5 Overview of the rule levels - the purpose of this section is to provide an understanding of the type of data validated at each level. This is an informative section to provide a short link to the QoCDC document.
- 6 Business process - this section describes the business process including the actors, the exchange of CIMXML documents, validation of IGMs and CGMs, creation and validation of IGMs, assembly and validation of CGMs and power flow calculations for capacity/congestion evaluation. Additional details are also provided in the “EMF requirement specification”.
- Chapter 7 XML format contains guiding information, descriptions and restrictions on the XML format.
- 8 Metadata - this chapter depends on QoCDC, describing the current and partly implicit metadata information.

Network system modelers and power system analysis engineers will find details on refinement of modelling of power system equipment in chapters 9 to 14, which discuss modelling issues discovered during analysis of IGMs and interoperability tests. These guiding sections are considered by the standardisation work so that the standards can be improved. Some issues can be solved by adopting one of several possible modelling styles.

3. Related Documents

The following documents are applicable:

[1] The IEC TS 61970-600-1/2:2017[5] is based on the Common Information Model (CIM) 16 (UML 16v29). The following documents defines the semantic model:

- IEC 61970-301:2016 Ed6[5]: Common Grid Model (CIM) Base
- IEC 61970-302:2018 Ed1[5]: Common Grid Model for dynamics specification
- IEC 61970-452:2017 Ed3[5]: CIM Static Transmission Network Model Profiles (i.e., the network equipment model)
- IEC 61970-456:2018 Ed2[5]: Solved Power System State profiles
- IEC 61970-453:2014 Ed2: Diagram Layout profile
- IEC 61970-552:2016 Ed2: CIM XML Model Exchange Format
- IEC 61970-501:2006 Ed1: Common Information Model Resource Description

[5] These standards or technical specifications are withdrawn in 2021 as updated versions are published by IEC. However due to SOC decision they will be used for some time and in parallel organizing transition to recent versions.

Framework

(CIM RDF) schema

[2] More restricting is the Common Grid Model Exchange Specification version 2.4.15 (here referred as CGMES v2.4) published as the specification IEC TS 61970-600-1/2:2017, providing context for ENTSO-E exchanges:

- IEC TS 61970-600-1:2017 Ed1[5]: Common Grid Model Exchange Specification
- IEC TS 61970-600-2:2017 Ed1[5]: Exchange profiles specification

[3] QoCDC - The validation rules are specified in the "Quality of CGMES Datasets and Calculations" (QoCDC) document, which also includes the file name convention for IGM files.

[4] The merging process, solving power flow on merged models (CGMs) and verify that the power flow solution is valid and safe is specified in the "EMF requirement specification" document. The document specifies requirements needed to enable a highly automated exchange process and univocal interpretation of exchanged network models for the CGM process.

[5] CGMA and PEVF specifications describe the schedule data used to create the inputs for solving power flows at every market time unit. The documents can be found at the ENTSO-E EDI library (https://www.entsoe.eu/publications/electronic-data-interchange-edi-library/).

[6] The ENTSO-E Scheduling System (EES) Implementation Guide v 4.1

[7] IEC 61970-301:2021 is the standard for the canonical information model used as basis for IEC 61970-600

[8] IEC 61970-600-1/2:2021 is the IEC standard based on CGMES 3.0.

[9] IEC 60633 Edition 2.1 Terminology for high-voltage direct current (HVDC) transmission

[10] HVDC Transmission Power Conversion Applications in Power Systems, IEEE press and Wiley & Sons.

[11] Network codes profiles/specifications.

[12] ENTSO-E Boundary and reference data exchange application specification (BRDEAS).

4. Definitions and abbreviations

Term	Description
Assembled model	An IGM is assembled by putting together CIMXML files tracing by the instance file header dependencies starting from the SV CIMXML file. A CGM is assembled by putting together the CIMXML files for the IGMs to be included in the CGM.
Boundary set (BDS)	A boundary set consists of the CIMXML files that conform to EQBD and TPBD profiles. For CGMES v3, TP boundary instance file is not necessary.
Market time unit	This is the term used for the schedule time steps in the network codes and methodologies. Same as scenarioTime in document header.
Bus Branch (BB) model	A network model using a simplified representation of a network. Detailed breaker bays are normally not described by cim:Switch-es and if cim:Switch-es are used they are flagged as retained.
Node Breaker (NB) model	A network model representing breaker bays with cim:Switch-es flagged as non-retained. Several levels of details are possible. The simplest is just describing breakers with cim:Breaker-s and the more detailed is also describing isolators and disconnectors with cim:Disconnector-s. Some cim:Switch-es may be flagged as retained in case the power flow across them need to be monitored, e.g., coupler bays.
TN	cim:TopologicalNode represents the power flow busses in a power flow model, defined as the single fictive point in a system at which several components of the power system like generators, loads, and feeders, etc., are connected. Normally, it is obtained after a topology processing algorithm, which creates the nodes considering statuses of switching equipment and zero impedance connections. Power flow calculation results such as voltage magnitude, phase angle of the voltage are reported on cim:TopologicalNode.
CN	cim:ConnectivityNode represents the electrical connection points in a network model. In CGMES v2.4, it is always used in NB models and could be used in BB models. Since CGMES v3.0, it is uniformly used for any kind of model. Note that NB models may have parts that are BB style where detailed switch modelling has not been used.
CGM	Common Grid Model. A power system model provided by a Merging Agent (e.g., an RSC/RCC). A CGM is assembled from IGMs for a market time unit of energy delivery day and time horizon, e.g., one day ahead.
CGMM	Common Grid Model Methodology
RSC	Regional Security Coordinator
RCC	Regional Coordination Centre
OPDM	Operational Planning Data Management is a file exchange service for remote clients. It is used to exchange CIMXML files as well as other files.

Term	Description
QAS	Quality Assurance Service
NMD	Network Modelling Database
Boundary point	Designates a connection point at which one or more model authority sets shall connect to. The location of the connection point as well as other properties are agreed between organizations responsible for the interconnection, hence all attributes of the class represent this agreement. It is primarily used in a boundary model authority set which can contain one or many BoundaryPoint-s among other Equipment-s and their connections. In CGMES v2.4 the boundary points are in the boundary set (BDS) and each boundary point consists of one - cim:ConnectivityNode in the BDS EQBD CIMXML file. - one cim:TopologicalNode in the BDS TPBD CIMXML file.
EI	cim:EquivalentInjection
IGM AC IGM DC IGM	Individual Grid Model. A network model provided by a Modelling Authority (e.g., a TSO). An IGM is a collection of CIMXML files for a market time unit of energy delivery day and a time horizon, e.g., one day ahead. There are two types of IGMs: - An IGM describing an AC power system possibly including simplified HVDC modelling, in this document labelled as an AC IGM. - DC IGM describing a detailed HVDC converter model according to the DC information model in CIM and described by its own MAS. Note that DC MAS is sometimes used to mean DC IGM. This is a misuse that is not recommended.
CGM BP	CGM Building Process is the process of building CGMs from IGMs.
BP ST	The Building Process Sub-Team of OPDE Task Team.
CGMES v2.4	The IEC Technical Specification IEC TS 61970-600-1/-2:2017.
CGMES v3	The IEC Standard IEC 61970-600-1/-2:2021.
Converter CSC VSC	The converter is the rectifier that converts AC into DC or the inverter that converts DC into AC. CSC stands for Current Source Converter with capability to control the active power transfer. VSC stands for Voltage Source Converter with capability to control both active and reactive power transfer.

Term	Description
HVDC Pole	An HVDC Pole has a DC cable with a converter at each end and is the smallest unit of equipment independently capable of transferring DC power, see also “Figure 2 Definitions as defined in IEC 60633”in [12]. In IEC 60633 a “HVDC Pole” is called a “HVDC system pole” and defined as part of an HVDC system consisting of all the equipment in the HVDC substations and the interconnecting transmission lines, if any, which during normal operation exhibit a common direct voltage polarity with respect to earth.
HVDC Bipole	It is part of an HVDC system consisting of two HVDC system poles, that could be operated independently. But during normal operation an HVDC Bipole controller coordinate the two HVDC Poles, so they exhibit opposite direct voltage polarities with respect to earth.
HVDC Link	An HVDC Link consists of one or more HVDC Bipoles and HVDC Poles. Large links may have several bipoles or poles also being of different technologies, e.g., CSC or VSC.
Point of common coupling PCC	From IEC 60633:2020 Point of interconnection of the HVDC converter station to the adjacent AC system.
PccTerminal	The PccTerminal is a cim:Terminal at a branch, e.g., a cim:Switch or a subclass of it, a cim:ACLineSegment, a cim:SeriesCompensator, or a cim:PowerTransformer where the active power flow from the HVDC Pole into the AC network is monitored.
PPD	Pre-processing data: a set of preliminary total net positions and unbalanced DC flows provided by a TSO to the CGMA platform to compute a reference program for the creation of IGMs for time horizons where no market data is available.
PSLC	Pole split and loss calculation: a process where the flows for DC links are split on the level of boundary points with loss correction and sent to CGMA or PEVF to be validated and to generate the final reference program.
“initial reference program” “final reference program”	Initial reference program is the output of the core CGMA process ending with the provision of balanced netted area positions and balanced gross flows on all (unsplit) DC links. Final reference program is the output of the PSLC of CGMA process, containing netted area positions and balanced flows on DC links (by considering poles and losses).
MAS	Modeling Authority Set that defines the origin (Modelling Authority) and purpose of an IGM.

Term	Description
Reference data Master data	Reference or master data is data that describes stable information that does not change frequently over time, e.g. - TSO and RSC/RCC names and id's - Countries and network regions - Boundaries between network regions
1D	Day ahead process.
2D	Two days ahead process.
ID	Intraday process.

5. Overview of the rule levels

The QoCDC document defines rules that are divided in levels where the lower-level rules must be passed before higher-level rules can be processed. The rules are organized in eight levels with complexity increasing at higher levels as listed in Table 1. The lower levels discover fundamental issues that blocks further processing. For CIMXML files to be useful they must pass levels 1 to 6.

Table 1 Validation levels

#	Level name	Level description
1	Meta data in file names	Level 1 checks CIMXML file naming, meta data in file names and file packaging. This level supports the automated file exchange and processing.
2	Structure syntax and metadata	Level 2 checks XML and RDFS validity, meta data in CIMXML file header and consistency with meta data in CIMXML file name. This level supports the automated file exchange and processing. Level 2 contains rules checking different types of data: - XML format issues. - Meta data issues. - Network model profile related issues.
3	Constraints and mapping	Level 3 checks the validity of objects in the scope of a single CIMXML file.
4	Model assembly	Level 4 checks that the meta data describing dependencies between CIMXML is consistent so that the files can be assembled. This level supports the automated file exchange and processing. Level 4 contains rules checking different types of data: - Meta data issues. - Network model profile related issues.
5	Consistency of assembled model	Level 5 checks that objects across CIMXML files for different profiles in an assembled IGM or CGM are consistent.
6	IGM and CGM plausibility	Level 6 checks that the power flow solution provides a good enough input for subsequent CGM assembly.
7	Coordination	Level 7 checks that the assembled IGMs in a CGM are consistent with each other as well as with market data (PEVF and CGMA files).
8	Convergence behaviour and CGM plausibility	Level 8 checks that the power flow calculation for IGM or CGM convergences and that the solution is plausible, e.g., stays within given limits.

6. Business process

6.1 Introduction

This section gives an overview of the assembly process and guides on how to specify meta data controlling the process and the exchange of data.

The roles appearing in the CGM building process are shown in Figure 1.

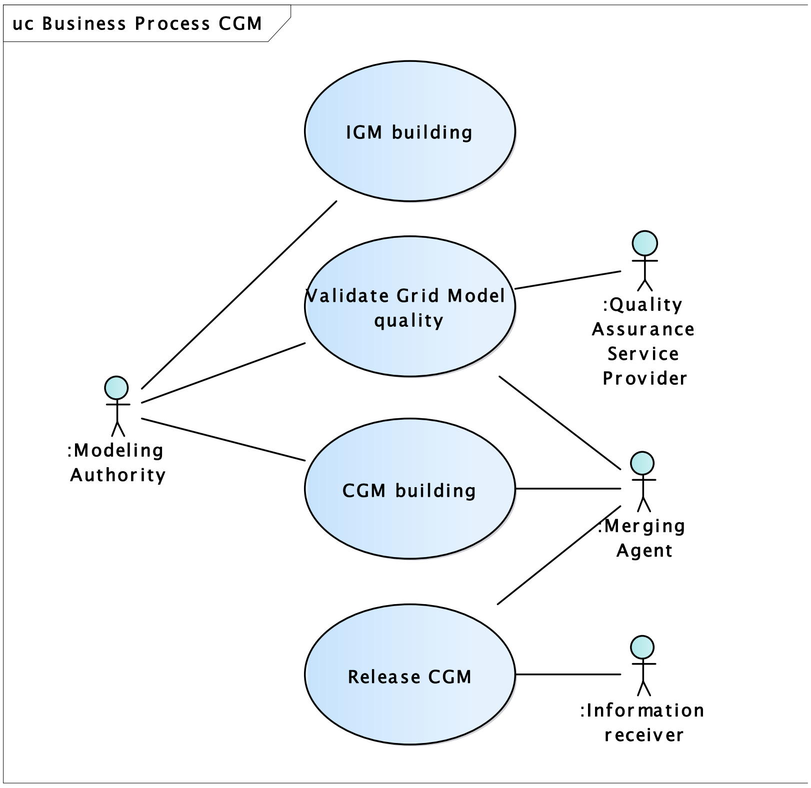


Figure 1 Use case diagram of the CGM building process

The roles involved in the CGM building process are:

- CGMA platform that provides aligned net positions and DC flows, and PEVF platform that provides schedules, for the respective energy delivery day, are not shown in Figure 1.
- Modelling Authorities (TSOs) that use the schedules to evaluate network security or transfer capacity for each time unit. This results in IGMs made available to other actors after validation by a Quality Assurance Service Provider.
- The Quality Assurance Service Provider validates IGMs and CGMs.
- Merging agents (e.g., RSCs/RCCs) are responsible for assembling IGMs into a CGM which is made available to Information Receivers after validated by a Quality Assurance Service Provider.
- Information Receivers are users of validated IGMs or CGMs. The use is typically to perform an analytical study with the IGMs or CGMs as base. Examples of Information Receivers are TSOs, RSCs/RCCs, ACER, etc.
- The interaction between the Alignment Agents and the Modelling Authorities (TSOs) is not covered by this document, but the interaction between Modelling Authorities and Merging agents is described. The steps in the interaction are shown in Figure 2 and Table 2.

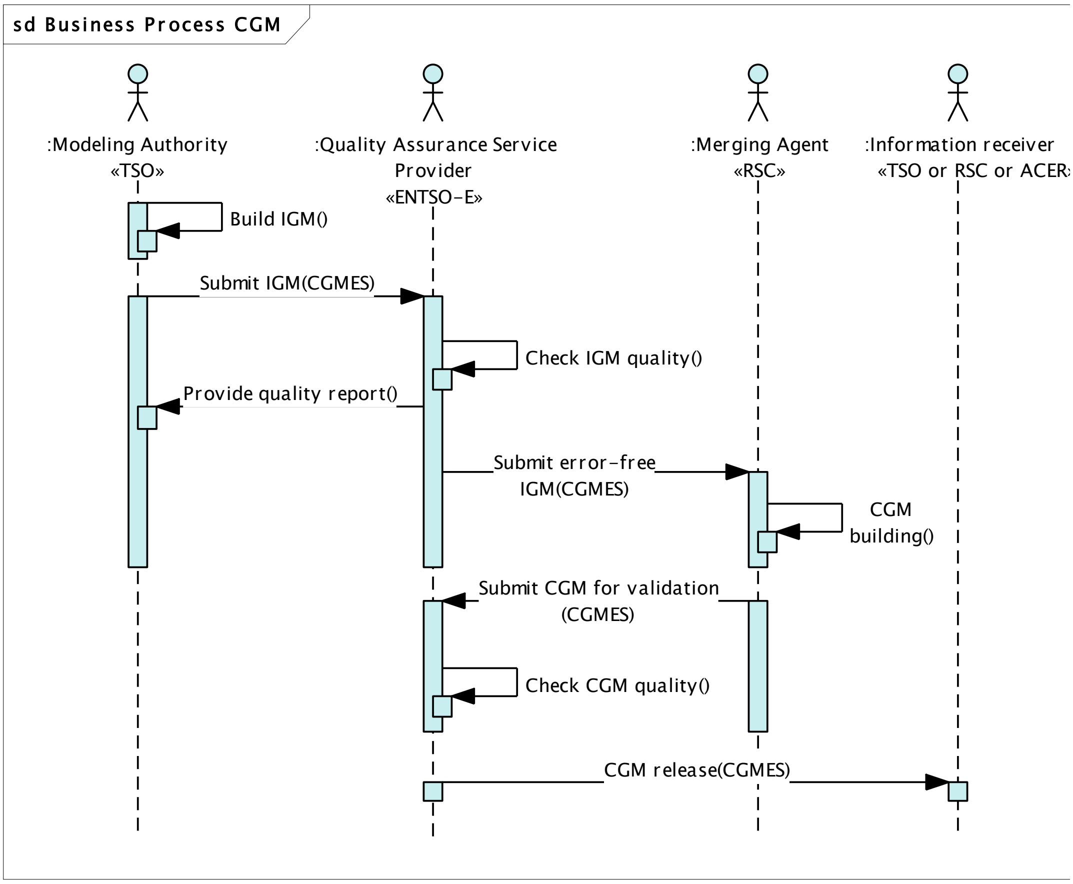


Figure 2 High level sequence diagram of the CGM building process

The power flow cases require that the network models have a well-defined boundary set that separates the IGMs. IGMs are non-overlapping and the boundary establishes electrical connection points (also called X-nodes based on UCTE area code legacy) between the IGMs, e.g. where tie lines connect. The boundary is described by two CIMXML files:

- EQBD profile - a boundary equipment instance file that contains all objects defined in the CGMES boundary equipment profile and includes data for boundary information relating to a given exchange.
- TPBD profile (CGMES v2.4) - a boundary topology instance file that contains all objects defined in the CGMES boundary topology profile and includes data for boundary information relating to a given exchange.

Boundary equipment (EQBD) and boundary topology (TPBD)[6] instance files, *referred together as boundary set (BDS) contain data needed to create an individual grid model (IGM) as well as to create a pan-European or regional model. The BDS is currently maintained centrally by ENTSO-E in the Network Modelling Database (NMD). As an interim solution, the duty of the BDS provision to OPDE has been delegated to one of the OPDE Operators, consisting of the monthly upgrade of the BDS provided by NMD in fit-for-purpose form, based on current requirements, making it available on OPDE and tagged as*

[6] For CGMES v3, information related to the TopologicalNode-s of the BoundaryPoint-s are included in the TP instance file of the IGM as they are not persistent due to topological process which is dependent on the status of the switches.

official for the purpose of CGM creation on OPDE. This fit-for-purpose transformation for the interim solution respects the following principle: no boundary point and tie-line data coming from NMD is changed, unless deemed necessary for the purpose of CGM process and the changes cannot be performed by the TSOs themselves. To fulfill the requirements of OPDE, the transformation may add data, which is not present in NMD, to boundary points and tie-lines. When the target solution is developed, there shall be no post processing on boundary and reference data (boundary point, base voltage, etc.). All changes shall be done in the source system following the agreed process.

The steps in Table 2 are further detailed in the following sections Table 2 Processing steps in tabular form

#	Step description
1	The Modelling Authority (TSO) receives market schedules on daily basis (process description is outside the scope of this document).
2	The Modelling Authority (TSO) uses a reference power system model consisting at least of its area of responsibility but can be extended to observability area that impacts the internal power flow. This power system model is used to extract the IGM which is under the Modelling Authority. Power flow is solved for each market time unit.
3	Modelling Authority (TSO) creates a set of CIMXML files for the solved power flow cases, an AC IGM that contains of: a) Equipment file (EQ) per region (if applicable), per business process (if relevant) with provision frequency spanning from “when change occurs” up to per market time unit. b) Topological processing and power flow solution and results for each market time unit which means that the solution appears in the following CIMXML files. i. One SSH CIMXML file that contains the power flow inputs e.g., switch statuses if present. ii. One TP CIMXML file that contains topology objects (fictive power flow busses) referencing the corresponding equipment and defining how the equipment is electrically connected. iii. One SV CIMXML file that contains the results of the power flow solution, see also section 6.4. For DC IGM the modelling Authority (TSO) creates one set of IGM files for each market time unit. A TSO that does not intend to exchange a detailed HVDC model will not create the DC IGM.
4	A Modelling Authority (TSO) submits CIMXML for validation to a OPDM client. Resulting quality assurance report (QAR) is provided to Quality Assurance Service (QAS) portal. Validation engine of OPDM client is validating IGM for all the rules in level 1-6, extracting data that will enable validation 7 in QAS and validation IGM for all the rules in level 8 except the load flow plausibility (EMF) validation rule. A Modelling Authority (TSO) CIMXML files (error-free in validation levels 1-6) are published to OPDE. If errors are detected in validation levels 1-6, the IGM is rejected and the TSOs can correct and submit their IGMs again.
5	Published Modelling Authority (TSO) CIMXML are made available to Merging Agent (RSCs/RCCs)..
6	A Merging Agent obtains the IGM CIMXML files for Modelling Authorities (TSOs).

#	Step description
7	A Merging Agent validates power flow plausibility of an IGM and provides a validation level 8 single rule report (EMF report) to QAS. If and IGM fails the power flow plausibility validation, it is validated with error severity and cannot be used in a merging process. If error is detected in powerflow validation in level 8, the TSOs can correct and submit their IGMs again, otherwise the missing IGM shall be substituted in merging process based on substitution rules.
8	The Merging Agent creates the CGM and power flow is solved for each time unit.
9	The Merging Agent provides the updated power flow inputs (SSH, for more details see section 6.6) per Modelling Authorities (TSO) and an SV for CGM for validation to OPDM client. Resulting quality assurance report (QAR) is provided to Quality Assurance Service (QAS) portal If error-free (in validation levels 1-6), CGM is published to OPDE and made available to Information receiver. If errors during validation (in validation levels 1-6) are detected, the CGM is rejected. The Merging Agent as well provides the level 8 CGM load flow plausibility validation report (EMF report) to QAS.

6.2 Overview of exchanged CIMXML files

The data exchanged in the workflow steps described in Table 2 is primarily CIMXML files for IGMs and CGMs. The CIMXML files for an IGM are listed in Table 3.

Table 3 CIMXML files in an IGM - power flow part

Type of CIMXML file	Appearance
EQBD Boundary Equipment	One for the Pan-European grid model[7].
TPBD Boundary Topology (CGMES v2.4 only)	One for the Pan-European grid model.
EQ Equipment, single file describing three EQ profiles[8]: - EQ Core - all equipment - EQ Operation - data needed by real time systems, e.g., SCADA/EMSs - EQ Short circuit - data needed by short circuit calculations	One per TSO (and region if applicable). Per business process (e.g., 1D, 2D) or without indication of business process if relevant for all. This data can be exchanged: - at least when it changes, following the established processes and restrictions imposed by the storage and archiving rules of the applications connected to the OPDE - at a fixed cycle with highest resolution of exchange for every market time unit.
SSH Power flow input	One per energy delivery day, business process, market time unit and TSO.
TP Fictive power flow busses	One per energy delivery day, business process, market time unit and TSO.
SV Power flow solution	One per energy delivery day, business process, market time unit and TSO.

A CGM is established/assembled as a result of CGM Building process in line with legal requirements arising from EU Network codes.

A CGM consists of several assembled IGMs and the CIMXML files describing a CGM are listed in Table 4.

[7] This is the present way of EQBD exchange. ENTSO-E Boundary and reference data exchange application specification defines use cases where exchange of multiple EQBD instance files is necessary to cover specific needs.

[8] In CGMES v3 there are three separate profiles - Equipment, Operation and ShortCircuit normally exchanged in one instance file. Operation and ShortCircuit instance data can be added if needed.

Table 4 CIMXML files in a CGM - power flow part

Type of CIMXML file	Source	Appearance
EQBD Boundary Equipment	BDS	One for the Pan-European grid model.
TPBD Boundary Topology (CGMES v2.4 only)	BDS	One for the Pan-European grid model.
EQ Equipment	IGM	One per TSO (and region if applicable). Per business process (e.g., 1D, 2D) or without indication of business process if relevant for all. This data can be exchanged: - at least when it changes, following the established processes and restrictions imposed by the storage and archiving rules of the applications connected to the OPDE - at a fixed cycle with highest resolution of exchange for every market time unit.
SSH Power flow input	IGM	One per energy delivery day, business process, market time unit and TSO. These files are from the original TSO's IGMs and are unchanged.
Updated SSH Power flow input (SSHupd)	CGM	One per energy delivery day, business process, market time unit and TSO. These files are updated SSH CIMXML files of TSO's IGMs and are specific to the CGM, for more details see section 6.6.
TP Fictive power flow busses	IGM	One per energy delivery day, business process, market time unit and TSO. These files are from the original TSO's IGMs and are unchanged, no CGM specific TP file exists[9].
SV Power flow solution	CGM	One per energy delivery day, business process, market time unit, RSC/RCC and region (synchronous area or Pan-European).

6.3 Data validity

Validity of CIMXML files and assembled models is checked by the Quality Assurance Service. Any reported error at levels 1 to 6 prevents the files from becoming available for further processing by Merging Agent.

The validity of data is checked against the CGMES and rules described in the QoCDC document.

[9] In CGMES v3 the TP instance file for the CGM is a single file produced by the EMF application.

The CGMES profiles are used to validate that exchanged data conforms to the class, attribute and role names defined in the CGMES profiles and that cardinalities are respected. The rules in the QoCDC document describe additional data and restrictions to the CGMES[10] necessary for the CGM building process and other business processes where the CGMs are used.

Figure 3 illustrates the description of the validation process seen from the input data side and necessary input data per validation levels.

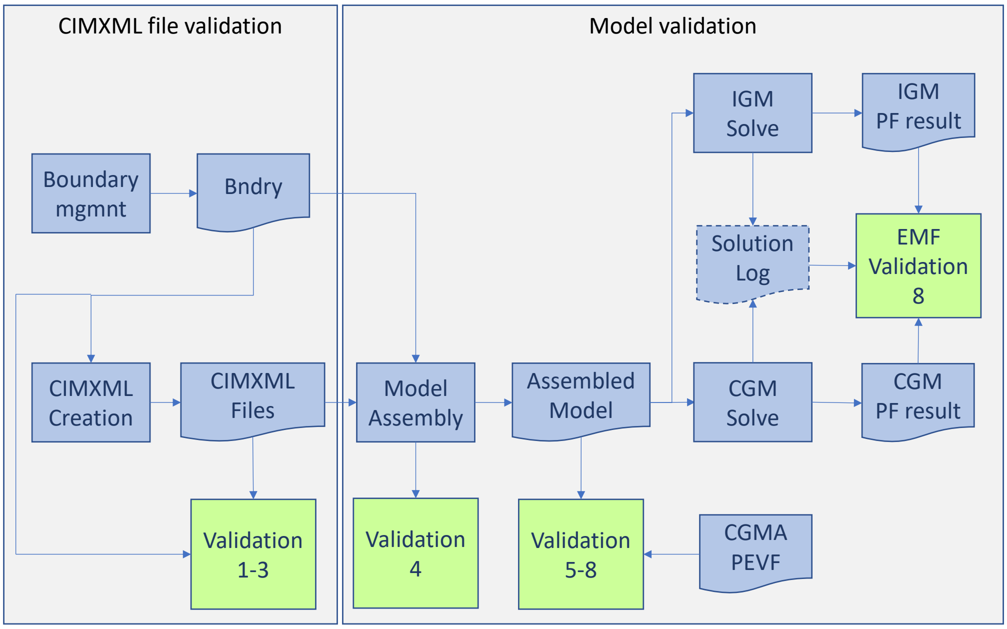


Figure 3 Validation levels concept for IGM and CGM[11]

The symbols in Figure 3 have the following meanings:

- Blue box – data processing (concept).
- Blue document – CIMXML file(s) or reporting market document file.
- Green box – validation.

The shaded backgrounds “CIMXML file validation” and “Model validation” show the scope for the validation per file and per model (IGM, CGM).

“CIMXML file validation” is done per CIMXML file, which means that the information in other CIMXML files is not used. This validation is done on simple data as name lengths but for EQ files more complex validation is done, e.g., attribute value ranges, curve data and limit values.

For “Model validation” all CIMXML files for an IGM or CGM are assembled into a model before

[10] In general, QoCDC should not specify additional requirements, but it should only restrict CGMES and add business specific constraints/rules which do not extend or modify the model. QoCDC for CGMES v2.4 presents few exceptions to this rule, which are acknowledged as such in the QoCDC document.

[11] Bndry (as Boundary Set), CGMA and PEVF (as reporting market documents) are considered as already validated input data.

validation is done. A complete model is assembled and validated for each market time unit. Model validation done for IGMs is not applicable for a CGM as the model is a new assembly with updated data. Hence model validation is repeated for a CGM. The CIMXML file validation (levels 1, 2 and 3) once done for an IGM can be trusted and do not need to be repeated for a CGM. A CGM contains new SSH CIMXML files for each IGM (see section 6.6 for details) and one new SV CIMXML file for the solution. These files are validated at levels 1-3. The CGM is validated at level 4 and up.

Errors at levels 1 to 6 will prevent an IGM to become available to a Merging Agent for further processing and creation of CGM, as well as for a CGM to become available to Information receiver (see Figure 2).

The "Boundary mgmnt" box represents the boundary files creation and management (irrelevant to implementation). Hence the "Bndry" represents the Boundary Equipment and Topology CIMXML files that are also validated at levels 1 to 4, but in Figure 3 they are considered as already validated input data. The "CIMXML creation" is where a TSO creates the CIMXML files, or Merging agent creates CGM CIM XML files (refer to Table 3 and Table 4). The result is the "CIMXML files" that are validated with level 1 to 3 rules.

When an IGM or a CGM is assembled it is checked that all necessary CIMXML files are available. This is done in "ModelAssembly" that checks the availability of CIMXML files according to level 4 rules.

The assembly results in an "Assembled Model" that is checked with level 5 to 7 rules. Level 7 rules check the consistency between IGMs and consistency of IGMs with the net positions in PEVF or CGMA documents.

Level 8 rules validate calculation results that assess the credibility of the power flow solution.

Level 8 EMF rules check the power flow result is plausible, the "IGM Solve" path corresponds to the process described in section 6.5 and the "CGM Solve" path corresponds to section 6.6.

6.4 IGM creation

A power flow solution described by CIMXML files uses the files depending on the profile as follows:

- EQ is an input to power flow describing the network
- SSH describes the power flow input parameters, e.g., injections and set point values.
- TP describes the fictive power flow busses and depends on the type of model:
    - For Node Breaker (NB) model's TP is an output from topology processing, Figure 48 shows an architecture for this. TP is an input to power flow calculation.
    - For Bus Branch (BB) model's TP is maintained in tools dedicated to this. TP is an input to power flow calculation.
- SV describes the power flow solution, so it is an output from power flow calculation.

The European power system is interconnected, which means that the impact from the neighbouring networks and market schedules need to be considered.

Creating an IGM for a TSO, means including parts of the neighbouring networks and market schedules. Hence, the power flow will usually be solved not only for the part of power system that is the area of the responsibility of a TSO, but also for a wider system of interest and impact. This means that the power system data for the IGM needs to be extracted from the wider power system model used when calculating the power flow for a specific scenario (time horizon, market time unit).

The boundary between the IGMs is described by boundary cim:TopologicalNode-s (TN) and boundary cim:ConnectivityNode-s (CN)[12].

Figure 4 gives a conceptual overview of the data flows and functions involved in the creation of an IGM.

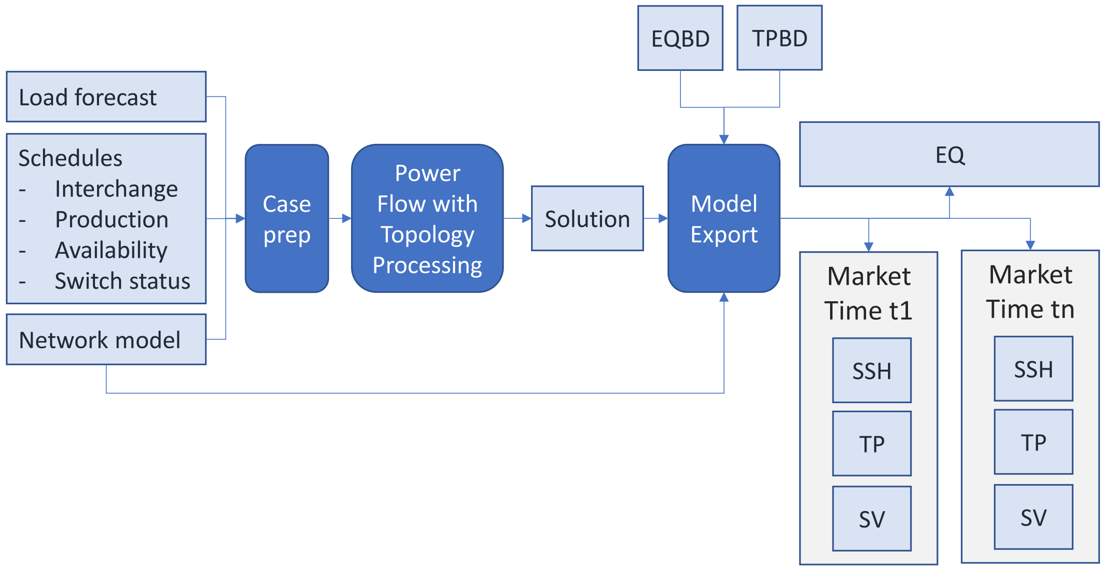


Figure 4 Creation of IGM CIMXML files[13]

Inputs to IGM creation are load forecasts and market schedules shown in Figure 4. From this data a power flow case is prepared for each time unit by the "Case prep" function, this corresponds to step 2 in Table 2. The case preparation also maps the schedules and load forecasts to the network model. This process is TSO's proprietary and specific, i.e., details are outside the scope of this document.

The "Network model" in Figure 4 is created by some data management tool, typically using a proprietary information model. When an IGM is created the data from this proprietary information model need to be converted to EQ CIMXML files which is represented by the arrow from the "Network model" to the "Model export". The "Model export" then creates all the CIMXML files as indicated in Figure 4.

Note that Figure 4 describes expected functionality and data flows between them. The functions outlined in Figure 4 can be implemented in numerous ways very different from Figure 4 so the figure should not be considered as a norm for implementations.

The power flow cases in Figure 4 are Node Breaker style and topology processing is used to compute the fictive power flow busses from the network model and switch statuses. After this, the power flow is solved and the solution including the fictive power flow busses is available as the "Solution" in Figure 4.

---

[12] In CGMES v3 there is a class eu:BoudnaryPoint used to identify which cim:ConnectivityNode-s are boundary points. For more details on the boundary definitions and requirements, please refer to CGMES and ENTSO-E Boundary and reference data exchange application specification.

[13] TPBD is only relevant for CGMES v2.4.

As discussed above, the power flow solution is usually for a power system area of interest and impact, i.e., not necessarily the model which will be exported as an IGM. The "Model export" function in Figure 4 extracts the IGM part of the solution and adapts it to the boundary described by the EQBD and TPBD (CGMES v2.4 only) CIMXML files. Figure 4 shows the case where the same EQ CIMXML file is exported for the power flow solutions for all market time units. The solution for each market time unit is described by one SSH, one TP and one SV CIMXML file, which corresponds to step 3 in Table 2.

Once the CIMXML files has been created they are provided for validation to OPDM Client and respective validation report is provide to QAS. CIMXML files that fail the validation in levels 1-6 and are rejected.

If CIMXML files for a market time unit have passed the validation level 1-6, they will be published to OPDE and made available to the Merging Agent. New CIMXML files may be created based on corrected inputs. Corrected CIMXML files have new md:FullModel rdf:about identifiers and md:Model.version numbers. The md:Model.version number are ascending and it is assumed that less than thousand revisions is needed per market time unit.

6.5 IGM power flow validity

An IGM power flow case is re-created by assembling its CIMXML files for a specific market time unit. The assembly uses the SV CIMXML file as starting point and traces the md:Model.DependentOn references to find which CIMXML files to include.

The CIMXML files are obtained by a Merging agent, this corresponds to step 6 Table 2. According to QoCDC document, dependent SV, SSH and TP CIMXML files in an IGM shall always have the same md:Model.scenarioTime. CIMXML files for the same profile and md:Model.scenarioTime may exist with different md:Model.version numbers, if so the one with the highest version number available shall be used.

IGMs that are available have been validated as described in section 6.4.

Once IGMs have been downloaded, they are used in subsequent power flow calculations. The SSH and TP CIMXML files are used as input. The initially provided original SV CIMXML is used for static validation, assembling, and can be used for cross validation of newly calculated SV CIMXML file that contains the new result as shown in Figure 5 for BB and NB models and Figure 6 only for NB models.

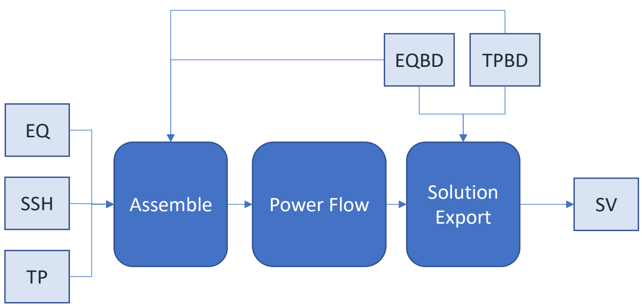


Figure 5 Concept of solving power flow using a BB tool[14]

Before power flow can be solved for a BB model the EQ, SSH, TP, TPBD and EQBD CIMXML files are assembled to a power flow case. The solved power flow is exported as an SV CIMXML file.

[14] TPBD is only relevant for CGMES v2.4.

The TP CIMXML file is a mandatory input only when topology processing is not used both for NB and BB models. A discussion on BB vs. NB models can be found in section 14.5.

In general, for a power flow to be solved for a NB model, it is sufficient that the EQ, SSH and EQBD CIMXML files are assembled to a power flow case. For the current design of CGM building process, in case of NB model as described in EMF requirement specification, TP CIM XML file shall also be considered as an input and the solved power flow is exported as one SV CIMXML file.

In case if potential full migration to NB models for all IGMs is accomplished, the processing of IGMs can be handled as shown in Figure 6. Note that the TP CIMXML file in the case of a NB model is an output if topology processing is used.

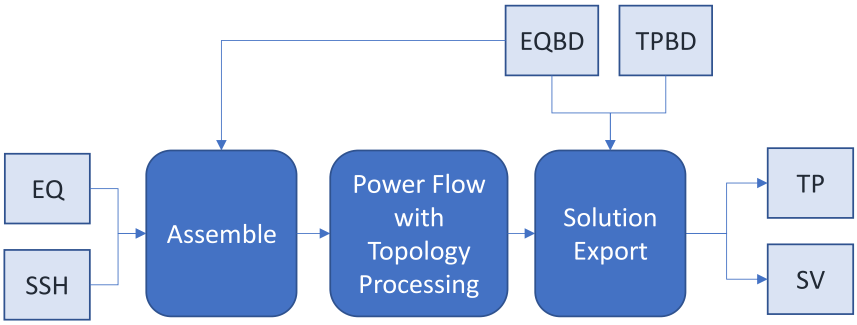


Figure 6 Concept of solving power flow using a NB tool with topology processing capability[15]

The settings to use when solving power flow on an IGM both for IGM creation process and validation of a power flow plausibility by Merging Agent are described in EMF requirement specification, among others:

- Generation slack using cim:GeneratingUnit.normalPF as distribution factor is used to maintain area interchange (proprietary definition resulting in the same behaviour in TSO's tools as well as the "IGM Solve" path in Figure 3 for validation process).
- Voltage control is enabled, and reactive power limits shall be respected.

Given that it was possible to solve the power flow, the solution in the SV CIMXML file shall not deviate from the starting values in the SSH CIMXML file, which is checked by the QoCDC level 6 rules.

A recommendation for a TSO to check the quality of its IGM is to import it and rerun the power flow as shown in Figure 5 or Figure 6.

An IGM that is found valid at validation levels 1-6, shall be made available for further processing, this corresponds to steps 4 and 5 in Table 2.

6.6 CGM creation

A CGM is created by assembling a set of IGMs. The assembly use the SV CIMXML file for the included IGMs as starting point and trace the md:Model.DepednentOn references to find which CIMXML files to include.

The IGMs are obtained by Merging Agent, which corresponds to step 6 Table 2. The obtained IGMs are validated for plausibility by solving power flow as described in section 6.5. After this

[15] TPBD is only relevant for CGMES v2.4.

the CGM is assembled and power flow is solved for each md:Model.scenarioTime. This corresponds to step 7 in Table 2.

If IGM is not available (e.g. invalid) for a particular md:Model.scenarioTime, a search for the best available substitution is done as described in EMF requirement specification. The EMF Requirements strictly define how, in case a valid IGM for a given md:Model.scenarioTime does not exist, the IGM can be substituted after gate closure time by another IGM with different md:Model.scenarioTime.

If substitution occurs, the CIMXML files comprising an IGM used for substitution have different md:Model.scenarioTimes compared to the md:Model.scenarioTime being studied. However, the substituting IGM is treated as it is from the md:Model.scenarioTime being studied.

As the Merging Agent is providing the updated SSH (containing a md:Model.Supersedes reference to IGM's original SSH CIMXML file) and one calculated SV as a result of CGM creation process, the difference in:

- md:Model.scenarioTime of the updated SSH, and
- md:Model.scenarioTime of the SSH CIMXML file of the IGM used for substitution

is an indicator that the substitution of the IGM happened.

When the IGMs are created (see Figure 4), different versions of the boundary set might have been used by different TSOs. The official version of the boundary set valid for the scenario time is used in the CGM creation and assembly. This process requirement is because a CGM is created by using only one boundary. The validation process of IGMs with the official boundary set is also established to make sure that a consistent set of boundary points master data is being used and CGM can be created.

Power flow of a CGM is calculated without topology processing resulting with new TP CIMXML file, which means that TP is used as an input, and it is not created as the result of CGM build process[16].

The inputs and outputs for power flow calculation when solving a CGM are shown in Figure 7.

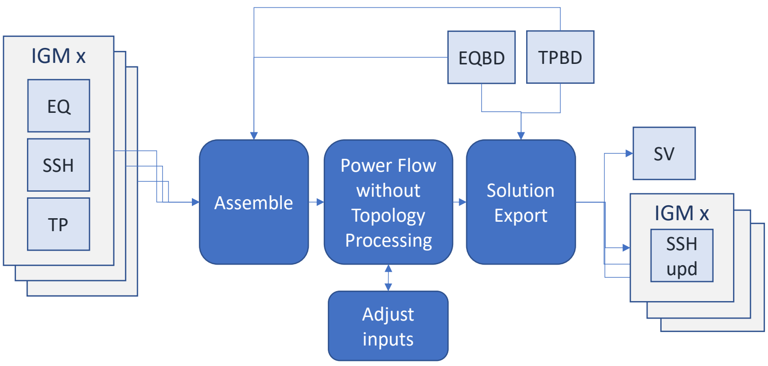


Figure 7 Concept of solving power flow for a CGM and one market time unit

After the CGM is assembled ("Assemble" in Figure 7), the power flow initial assumptions (SSH) might be adjusted as part of merging process and area interchange control thus updated SSH CIMXML files (SSHupd) are created. Adjustments ("Adjust inputs" in Figure 7) appears before the

[16] There is a difference here for CGMES v3 where TP is a common TP instance file for the whole CGM.

power flow is solved (e.g. aligning the status of interconnectors), while the power flow is solving (e.g. due to set limits and constraints for the power flow and area net interchange algorithms) and after the solution (aligning the SV and SSHupd values).

In case a valid IGM was not provided for the requested timestamp (md:Model.scenarioTime) before gate closure time, substitution algorithm will be applied as described previously.

The adjustments before power flow calculation are:

- Alignment of tie lines statuses if not aligned before gate closure time, resulting in disconnecting both sides of the interconnector simulating the worst-case scenario.
- For a partial assembly, that might occur if a synchronous area has gaps in case substitution algorithm did not result in selection of an IGM for substitution (e.g. IGMs were not provided for longer period of time) boundary tie lines for the missing IGMs cannot be matched by an IGM at the remote end of the tie line. The flow in unmatched tie lines are represented by injection values at cim:EquivalentInjection-s and may need adjustment as follows:
- DC tie flows are adjusted according to market schedule if available and applicable.
- The sum of the flows both for AC and DC at the cim:EquivalentInjection-s (of the tie lines which are only defined on one IGM's side and for which a cim:TieFlow exists) shall match up with the sum of the net positions (cim:ControlArea.netInterchange attribute) in the assembled CGM. If this is not the case those AC cim:EquivalentInjection-s must be scaled so they match sum of the net positions. The power factor shall be maintained when scaling. The cim:TieFlow-s included in the summation shall be linked to a cim:ControlArea of type interchange.

The adjustments while solving a power flow are made to respect the limits and constraints and to maintain the active power exchange for cim:ControlArea. The active power flow exchange for each cim:ControlArea shall match the net interchange. Any mismatch that appears per cim:ControlArea is distributed as load slack over the cim:ConformLoad-s in the cim:ControlArea.

The power flow is solved with agreed settings:

- Two different algorithms for controlling active power interchange of cim:ControlArea-s are available:
- Equations are embedded in the power flow solver including equations for distribution of mismatch over cim:ConformLoad-s, this is load slack.
- A classic area net interchange that distributes mismatch between iterations over cim:ConformLoad-s until all scheduling areas are inside the defined offset threshold per area, simulating a load slack. The residual threshold mismatch is distributed on all generating units in the CGM proportional to the reserve margin for each unit, this part of the classic algorithm is generation slack.
- Voltage control is enabled, and reactive power limits shall be respected.
- Active power control is enabled, and active power flows shall be respected.

Once the power flow is solved, the updated SSH files are exported ("SSHupd" in Figure 7) with the following adjustments and results:

- The scaled injections for cim:EquivalentInjection-s at the borders of the CGM.
- The computed tie line power flows at the cim:EquivalentInjection-s inside the CGM.
- The cim:ConformLoad injections resulting from load slack distribution.
- Reactive injections at cim:SynchronousMachine-s (cim:RotatingMachine.q attribute) as a

result of keeping voltage targets.

- Tap changer positions and shunt sections (cim:TapChanger.postion and cim:ShuntCompensator.section attributes) as a result of keeping voltage and active power flow targets.
- The active power injections from cim:SynchronousMachine-s are not updated in order to properly reflect the operating assumptions from the market regarding the generation schedules. The generation slack adjustments shall be small and not impact the operating assumptions.
- The other values in the SSHupd files are kept the same as in the original SSH files.
- The SV file includes the complete solution which is resulting from the usage of the updated SSH (SSHupd).

The power flow solutions in a CGM are created for each market time unit relevant for the business process. This means that a CGM for each studied md:Model.scenarioTime will have:

- one SV CIMXML file with a md:Model.scenarioTime representing the studied time.
- one SSHupd CIMXML file per IGM with the same md:Model.scenarioTime as the SV CIMXML file. Note that if an input IGM was substituted, SSH CIMXML file as part of the IGM used for substitution will have a md:Model.scenarioTime that differs from the studied time as recorded by md:Model.scenarioTime in the SV and SSHupd files. The replacement process is described in detail in the EMF requirements document. The SSHupd CIMXML file in case of the substitution has a md:Model.Supersedes reference to the original SSH CIMXML file that shall be a clear indication that the substitution happened.
- The version number for all created SSHupd and SV CIMXML files shall be the same.
- CGM SSHupd or SV CIMXML files may need recalculation due to issues in IGM CIMXML files at one or more time units, refer to section 6.4. New CGM SSHupd and SV CIMXML files shall then be created with new md:FullModel rdf:about identifiers and md:Model.version numbers. The md:Model.version number shall be ascending and all recalculated CIMXML files for a time unit shall have the same version number.

6.7 Checking security of a power flow solution

Once an IGM or CGM power flow solution has been created for the base case or a contingency case it is checked against operational PATL limits. Both voltages and branch flows are checked, the rules are at validation level 8. For branches the permanent admissible transmission loading (PATL) limits are used. Violations indicate that the power system is not congestion free with the given schedules and remedial actions must be taken to move the power flow solution within limits.

7. XML format

7.1 Introduction

This section provides information on the CIMXML format.

7.2 The Prolog

The prolog is defined in the CGMES and in IEC 61970-552. It contains information on the xml version and the encoding of the file. It is the statement seen at the top of the CIMXML instance file before the start of the RDF set of triples. For instance:

<?xml version="1.0" encoding="UTF-8"?>

QoCDC has some rules to check if the prolog contains required information.

7.3 XML name spaces

XML namespaces are used to make a vocabulary globally unique and avoid mixing it with other vocabularies. For instance, the word “Substation” may appear in many different vocabularies and assigning it to a namespace prevents mixing. So instead of just having the word “Substation” as element name it includes a namespace, e.g., “http://iec.ch/TC57/2013/CIM-schema-cim16#Substation”. For better readability the namespace can be replaced by a prefix, i.e., “cim:Substation” in the CIMXML instance file. When an element or an attribute name with a prefix is processed the software parsing the CIMXML replaces the prefix with the full namespace. To support this replacement a namespace declaration shall be present in an XML file, e.g.

xmlns:cim=”http://iec.ch/TC57/2013/CIM-schema-cim16#” (CGMES v2.4)

The use of namespaces in CIM standard is specific. Each CIM version has its own name space declaration. Note that this applies for each CIM version prior CIM18, e.g., for CIM17 (CGMES v3) the namespace is

xmlns:cim=http://iec.ch/TC57/CIM100#.

A consequence is that CIMXML files for different CIM versions cannot be mixed. Software reading CIMXML files need to manage the different CIM versions separately, e.g., quality gates and merging tools will have to read CIMXML files of different versions as separate sets. Hence boundary CIMXML files need to exist in one set per CIM version. Custom XML processing software might ignore this, but any solution based on W3C XML standards will not.

It is technically possible to mix data described by different CIM versions by having different CIM namespaces within the same CIMXML file and different prefixes for them, e.g., a cim16 URI and cim17 URI.

It shall also be noted that profiles do not have their own name spaces. This makes mixing data from different profiles simple as the same namespace is used given the CIM version is the same. The downside is that validation cannot use the CIM namespace but must rely on the md:Model.profile element in the md:FullModel header. However, the CIMXML format (described in IEC 61970-552:2016) is based on RDF technology and RDF compliant software natively can validate CIMXML files against profiles, or rather an ontology generated from the profile.

CGMES v2.4 uses the following namespace prefixes:

- “cim:” for power system data, defined in IEC standards for the canonical CIM and not for the profiles.
- “entsoe:” for ENTSO-E extensions to power system data, see CGMES v2.4[17]. Note that this namespace originates from extensions of the canonical CIM and not the profiles.
- “md:” for meta data for the Model header, see IEC 61970-552:2016.
- “dm:” for the difference model, see IEC 61970-552:2016.

Project specific implementations can contain other namespaces and related prefixes, such as cgmbp that is used for additional information in boundary set. Such solutions are normally

[17] Because CGMES v3 is an international standard, extensions are using prefix eu instead of entsoe.

temporally solutions until a standardised approach is defined and implemented.

8. Metadata

8.1 Introduction

Restrictions on metadata and business process are described by the levels 1, 2 and 4 rules. If any of these rules fail it is not possible to create a model that can be solved by power flow calculation. For levels 1 and 2 all information is in QoCDC. For level 4 guidelines are provided in following subchapters.

8.2 Guidelines on dependencies

The CIMXML header (either classes md:FullModel or dm:DifferenceModel) describes main content of the CIMXML instance file and its dependency on other instance files. QoCDC level 4 rules describe and restricts the required references between CIMXML files. The purpose is to support assembly of IGMs and CGMs. The assembly process always starts from the SV file and by tracing the dependencies starting from the SV file a complete IGM or CGM is obtained.

For CGMES v2.4 the dependencies are described in IEC 61970-552:2016[18] by the roles:

- md:Model.Supersedes.
- md:Model.DependentOn.

The required dependencies for md:Model.DependentOn are shown in Figure 8. Note that more references can exist between objects in different CIMXML files. However, the references shown in Figure 8 are the ones needed to successfully assemble and IGM or CGM.

Note that the boundary references in the SV and EQ files relate to the boundary files used when the IGM or CGM was created. When creating a CGM the official boundary files are used by the EMF application. Therefore, TSOs should ensure that changes in official boundary set are taken into account when IGMs are created.

For CGM process, the md:Model.Supersedes is restricted to the following use cases:

- Update of the same limit values multiple times (see example in Figure 9), only for CGMES v2.4 as limit values are in the EQ.
- Update of SSH files at CGM creation, with SSHupd, see example in Figure 10.

The possibility to exchange EQDIFF CIMXML files via OPDE is not implemented. Therefore, explanations are based on general CGMES terms and not specific CGM building process procedures. In case CGM process needs to include a possibility to exchange periodic update of operational limits, e.g., daily or hourly, an update of limits’ values in SSH is the recommended approach. This solution is available in CGMES v3 SSH.

[18] Descriptions are available in the standard and CGMES v2.4. CGMES v3 also relies of the same standard.

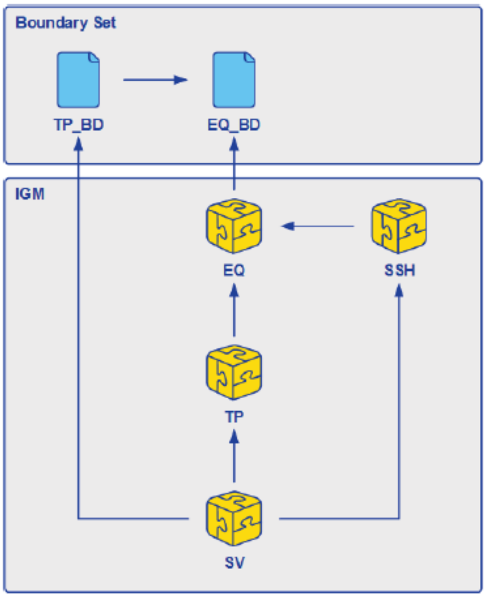


Figure 8 CIMXML file md:Model.DependentOn dependencies[19]

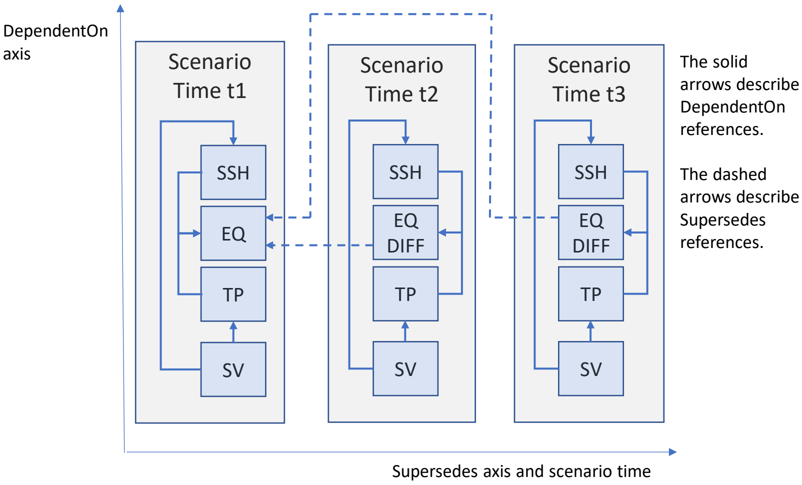


Figure 9 Use of md:Model.DependentOn and md:Model.Supersedes in IGMs

Figure 9 shows IGM power flow cases at three different scenario times (md:Model.scenarioTime) and the CIMXML files for each scenario time. The IGM for scenario time t1 has CIMXML files for EQ, SSH, TP and SV but without the boundary files. The IGM for scenario time t2 has an EQDIFF CIMXML file instead of an EQ CIMXML file. As the EQDIFF CIMXML file at t2 describes changes to the EQ CIMXML file at t1 the md:Model.Supersedes is the reference that links them together. The complete EQ CIMXML file for t2 is created by applying the changes in the t2 EQDIFF CIMXML file to the t1 EQ CIMXML file.

The relations between IGM and CGM CIMXML files is shown by the example in Figure 10.

[19] TPBD is for CGMES v2.4 only.

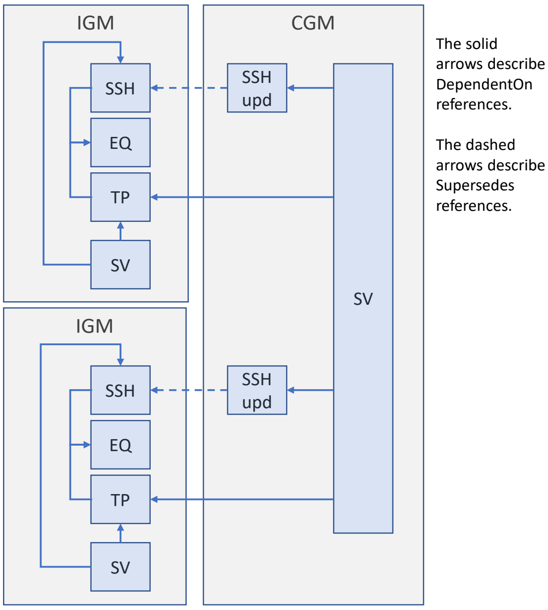


Figure 10 Example of relations between IGM and CGM files[20]

Figure 10 shows two IGMs to the left and one CGM created based on the IGMs to the right. The IGMs and the CGM are for the same scenario time (md:Model.scenarioTime). In case an IGM is missing for this scenario time, another IGM is used according to the replacement strategy applied for CGM creation process.

It can be noted that:

- The CGM relies on the CIMXML files from the IGMs.
- The CGM SV CIMXML file have md:Model.DependentOn references to the TP CIMXML file for each IGM.
- The EQ CIMXML files of the IGMs are located with the md:Model.DependentOn reference between TP and EQ.
- An updated SSH CIMXML file is created by the EMF application for each SSH CIMXML file in the IGM and they are linked to the SSH from the IGM with md:Model.Supersedes.

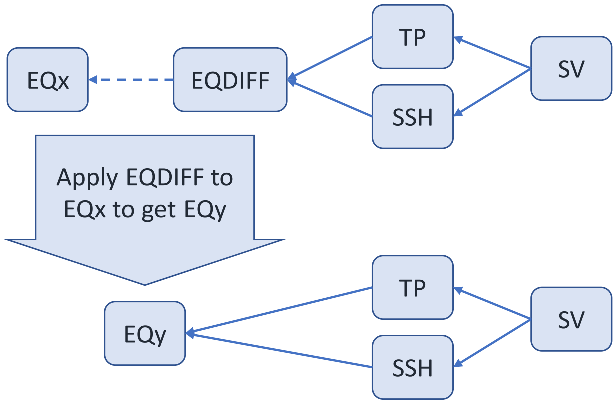
Usage of CIMXML difference file also requires usage of md:Model.Supersedes in the dm:DifferenceModel element to indicate to which model this difference model is applied to. In general, the operations to be applied are:

- Addition of new objects;
- Deletion of existing objects;
- Update of existing objects.

Note that CGM building process only supports using the dm:DifferenceModel for the purpose of updating limit values in EQ and this is only applicable for CGMES v2.4.

The operations using difference CIMXML files result in a new EQ model that contains the combination of superseding and the superseded files as shown in Figure 11. The new EQ model can be exported in a md:FullModel CIMXML file if this is required by the process.

[20] In CGMES v3 there is only one TP instance file representing the output of the topology process for the CGM.



DependentOn is described by non dashed arrows
Supersedes is described by dashed arrows

Figure 11 Application of DIFF files

In Figure 11 the EQ CIMXML file EQx is superseded by the EQDIFF CIMXML file. Applying the differences results in a new EQ CIMXML file EQy. EQy has the same meta data as EQDIFF which means the mRID, scenario time, description, profiles, MAS etc. are the same. The mRIDs being the same means that the rdf:about in the headers is the same. Hence the DependentOn references from TP and SSH to the original EQDIFF are not affected and work with the new EQy. Note that this is only valid because the scope of the EQ difference is limited to updates of limits' values only.

The discussion above indicates that the application of the difference EQDIFF is made with the files, but this is just one option. Places where a difference CIMXML file can be applied are:

- Before uploading CIMXML files to a middleware which means that no difference files are uploaded. This option is not used.
- By the middleware after upload as shown in Figure 12.
- By the receiving client after download from the middleware. This option is not used.

Figure 12 shows the application of an EQDIFF CIMXML file to the EQx file by the middleware (OPDE in this case) which means that Receivers do not see the EQDIFF CIMXML file but only the resulting EQy CIMXML files.

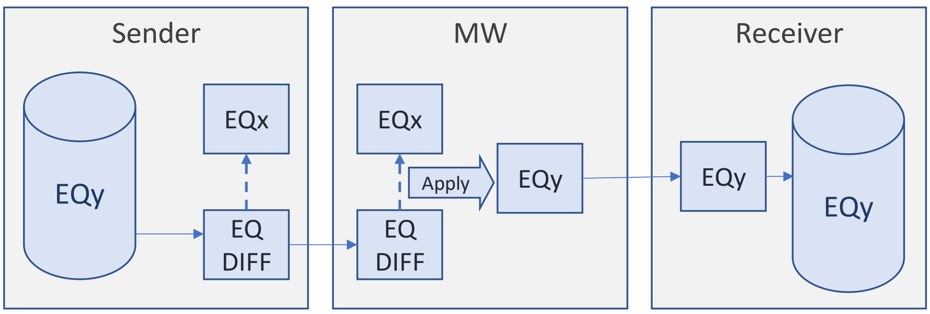


Figure 12 Applying the EQDIFF at the Middleware

In Figure 12 the EQDIFF CIMXML file is transferred to the middleware (OPDE) where it is applied to the EQx CIMXML file referenced by the md:Model.Supersedes in the difference file. This result, the EQy CIMXML file, can be downloaded by the Receivers.

Applying difference files at the middleware is also required for the validation as EQDIFF CIMXML files cannot be validated on their own.

The completeness of data across CIMXML files are checked at level 4 which includes two types of checks:

- The references between objects resolve, i.e., an object referenced by a rdf:resource exists.
- Objects are complete meaning that all mandatory attributes or references are present according to cardinality rules in the information model.

9. Boundary data

For details on boundary data and different configurations related to the boundary points placement for AC and DC IGMs, please refer to ENTSO-E Boundary and reference data exchange application specification.

10. Market schedule interface

10.1 Overview

To reflect the agreed power exchanges between the system operators in the forecast models, simulating the load frequency control and commercial electricity trade, the net position values for the corresponding market time unit are enforced by scaling algorithms over the scheduling areas of a CGM.

Agreed power exchanges are determined via scheduling process, which starts with the day-ahead schedule nomination of market participants and ends with the last intra-day schedule adaptations prior to real time operation. The scheduling process is ensuring that the sum of scheduling area's net positions within a synchronous area is equal to zero, i.e., net positions are balanced. The function that receives scheduled exchanges at the relevant time instances per scheduling area or per scheduling area border and per HVDC links and provides balanced net positions is Pan-European Verification function (PEVF). Balanced net positions are main requirement that enables the merge of IGMs into the CGM.

As market schedules are available only for day-ahead and intraday time horizon, the Common Grid Model Alignment process (CGMA) was established to make sure that it is possible to create CGMs for other time horizons, starting from two days ahead up to year ahead.

10.2 Market Data Messages

10.2.1 Reporting Information Market Document Format

The standardisation of the scheduling and alignment process information exchanges from PEVF and CGMA platforms to OPDE is based on the Reporting Information Market document, targeted towards business-to-business application interfaces.

Both PEVF and CGMA platforms have production and acceptance instances. The origin of the documents is indicated by the EIC of the sender (sender_MarketParticipant.mRID) in the document header. Respective documents are to be used with the grid models originating from the same OPDE environment, production or acceptance (see Table 5 for sender_MarketParticipant.mRID).

949 **Table 5 ReportingInformation_MarketDocument header**

	PEVF		CGMA
	Day Ahead	**Intraday**	**Two Days Ahead … Year Ahead**
ReportingInformation_MarketDocument			
xmlns	reportinginformation_marketdocument:2:0		reportinginformation_marketdocument:2:0 reportinginformation_marketdocument:2:1
mRID	Document identification		
revisionNumber	Version of the document		
type	B19 = Reporting information market document with virtual scheduling areas		B19 = Reporting information market document without PSLC B29 = Reporting information market document with PSLC
process.processType	A01 = Day ahead	A18 = Total intraday	A33 = Year ahead A32 = Month ahead A31 = Week ahead A45 = Two days ahead
sender_MarketParticipant.mRID	The role of the sender: 10V1001C--00012J = PEVF PROD 10V1001C--000365 = PEVF ACCE		The role of the sender: 10V000000000011Q = CGMA PROD 10V000000000010S = CGMA ACCE
sender_MarketParticipant.marketRole.type	A32 = Market information aggregator		A39 = Data provider
receiver_MarketParticipant.mRID	The role of the receiver, EIC		The role of the receiver, EIC
receiver_MarketParticipant.marketRole.type	A33 = Information receiver		The role of the receiver
createdDateTime	UTC time of document creation.		
domain.mRID	A scheduling area representing the regional group identified with an EIC Y code. codingScheme = A01.		The optimisation area of concern or the whole CGMA area identified with an EIC Y code. codingScheme = A01.
time_Period.timeInterval	This information provides the start and end date and time of the period covered by the document. A single whole calendar day in the CET/CEST time zone in UTC time. The time interval shall conform to the following pattern: YYYY-MM-DDThh:mmZ/ YYYY-MM-DDThh:mmZ		
docStatus	The identification of the condition or position of the document with regard to its standing. A document may be intermediate or final. A01 = Intermediate A02 = Final (to be used in processing)		

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Table 6 ReportingInformation_MarketDocument.TimeSeries elements

	PEVF		CGMA
	Day Ahead	**Intraday**	**Two Days Ahead … Year Ahead**
TimeSeries			
mRID	Identification of the time series		
businessType	B63 = Aggregated netted external schedule B64 = Netted area AC position B65 = Netted area position. The net AC and DC position of the scheduling area.		B64 = Netted area AC position B65 = Netted area position. The net AC and DC position of the optimization area. B67 = DC net flow at the importing end B68 = DC gross flow at the exporting end B73 = Indicative AC flow For CGMA in PEVF notation, see details for PEVF
product	8716867000016 = Active Power		
in_Domain.mRID / codingScheme	An area where the product is being delivered. Identified with an EIC Y code. Either the in_Domain.mRID or the out_Domain.mRID must match the subject_Domain.mRID. codingScheme = A01.		
out_Domain.mRID / codingScheme	An area where the product is being extracted. Identified with an EIC Y code. Either the in_Domain.mRID or the out_Domain.mRID must match the subject_Domain.mRID. codingScheme = A01.		
connectingLine_RegisteredResource.mRID	Required if DC link or controllable AC link codingScheme = A01 (EIC-T) Not used for: B64 = Netted area AC position B65 = Netted area position		
	Indication of DC link or controllable AC link.		Identification of the DC link on the level of poles and optionally of the DC link itself. Mandatory for: B67 = DC net flow at the importing end and B68 = DC gross flow at the exporting end Not used for: B73 = Indicative AC flow.
measurement_Unit.name	MAW = Mega watts		
curveType	A03 = Variable block		A02 = Point
marketObjectStatus.status	Not used		A32 = Result The values are the result from the CGMA optimization for netted AC area position and result from the PSLC for DC flow
TimeSeries.Period			
resolution	PT1M		Resolution used in the Point class. PT1H.
TimeSeries.Period.Point			
position	Position in the time series.		
quantity	Value of the netted (AC) area position or flow (no signed value).		
TimeSeries.Reason			
code	The following code shall be used: A28 = Substitution is applied A26 = Default Time Series applied A30 = Imposed Time Series from nominated party's Time Series A54 = Global position not in balance A88 = Verification succeeded B08 = Data not yet available. B30 = Data unverified B31 = Data verified Other reason codes according to ENTSO-E code list		Not used

10.2.2 PEVF

Each instance of PEVF platform is providing reporting information market documents of type = B19, per scheduling day, for the two time horizons (day ahead and intraday) and with multiple versions. Each evolution of PEVF document is carried out through the creation of a new version. The new version replaces the previous version.

Day ahead values of the schedules with business type of “Day ahead” being process.processType = A01. Two versions of this document are provided:

- Preliminary reference program (docStatus.value = A01) and version 1 (revisionNumber = 1) at 16:30h CE(S)T
- Final reference program (docStatus.value = A02) and version 2 (revisionNumber = 2) at 17:50h CE(S)T

Final reference program is used for the validation and CGM creation in day ahead process.

Intraday values of the schedules are with business type of “Total intraday” being A18. Thirty (30) versions of this document are provided for every intraday market gate, for a given market time unit (MTU). Allowed MTUs are 1/4h, 1/2h, 1h. The publication of PEVF documents to OPDE for intraday is on the hourly basis (at the moment).

- All intraday PEVF documents have the indication of preliminary reference program (docStatus.value = A01) as they start as the updated values of the values already provided in the day ahead PEVF document and continue as the updated values.
- The Time_Period.timeInterval and the timeInterval_DateTimeInteval always cover the complete period meaning the whole day.
- Versioning is ascending, with version 1 (revisionNumber = 1), published at 18:30h CE(S)T on the day before intraday process. The last, 30th version of the intraday PEVF document is published at 23:30h CE(S)T on the day of the intraday process.
- Intraday IGMs created for reference hour hh CE(S)T and available at OPDE by hh-0:55 CE(S)T, should be built with the market data available at hh-1:30 CE(S)T.
- In QAS, IGMs will be validated (and re-validated) against the latest available version of intraday PEVF document.
- For static validation, the cross validation of IGM against PEVF document should be with the version that is used for the intraday CGM creation.
- Intraday CGM creation at hh CE(S)T will use the latest available PEVF document published at hh-00:30 CE(S)T and be validated against the following PEVF documents:
- In QAS, the same or latest published version PEVF document, depending on the CGM publication time, and revalidated with every new version of PEVF document.
- For static validation, the PEVF document used for CGM creation should be used for CGM validation.

The PEVF document contains:

- Information on the area netted position (Netted area AC and DC position = B65).
- Information on the area net position (Netted area AC position = B64). Two (2) TimeSeries per scheduling area are provided. One TimeSeries provides the input to the area and the other provides the output from the area. One of the areas in the TimeSeries (in_Domain.mRID / out_Domain.mRID) is always the EIC Y code of the respective synchronous area. The other area in the TimeSeries is the EIC Y code of the TSO’s control area, corresponding to the cim:ControlArea in an IGM for which the value of cim:ControlArea.type is cim:ControlAreaTypeKind.Interchange.
- Information on the flows per border(s) (Aggregated netted external schedule = B63):
- Two (2) TimeSeries per scheduling area border, in_Domain.mRID / out_Domain.mRID are the EIC Y code of the involved AC scheduling areas, corresponding to the

cim:ControlArea(s) in the two IGMs for which the value of cim:ControlArea.type is cim:ControlAreaTypeKind.Interchange.

- Four (4) TimeSeries per scheduling area border, for DC links and controllable AC links.
  - Two (2) TimeSeries are assigned to the first of the involved TSOs and two (2) additional TimeSeries are assigned to the second involved TSO.
  - One of the in_Domain.mRID / out_Domain.mRID are the:
    - EIC Y code of the involved AC scheduling areas (TSOs) corresponding to the cim:ControlArea-s in the AC IGMs for which the value of cim:ControlArea.type is cim:ControlAreaTypeKind.Interchange
    - EIC Y code of the virtual scheduling area (VSC).
- DC links and controllable AC links are identified using additional "path"-information, connectingLine_RegisteredResource.mRID being the EIC T code of the DC link or pole, or controllable AC link.

As a conclusion, PEVF document and "PEVF notation" CGMA document, are based on using the same business types for AC and DC border exchange (businessType = B63) and the concept of virtual scheduling area with addition of connectingLine_RegisteredResource.mRID to define a DC link/pole (depending on number of boundary points defining the link) and AC controlled links.

With the combination of businessType (B63) and the EIC T code of the DC link/pole connectingLine_RegisteredResource.mRID, provided as well in the Boundary Data Set, the information is mapped to one of the ends of the DC link/pole, determined by the EIC Y code of the AC scheduling area in in_Domain.mRID / out_Domain.mRID of B63 TimeSeries.

Amongst all the time series descriptive information, there is as well the information of the curveType used to describe the type of curve that is being provided for the Time Series in question. In case of PEVF document, the curveType A03 – "Variable Sized Blocks" is used (see 10.2.4).

The validity of the information provided in PEVF document is determined based on the TimeSeries.Reason codes (see Table 6 for details). Missing or not validated scheduling data is flagged with the respective reason codes. If the values for DC links are missing or not validated, the validation shall be skipped.

10.2.3 CGMA

The CGMA platform calculates the CGMA results, which for core CGMA process consist of a set of:

- balanced netted area AC positions (businessType = B64)
- balanced netted area positions (businessType = B65)
- balanced gross DC flows at the exporting end (businessType = B68), on the level of poles or link (if poles are aggregated)
- indicative AC flows per border (businessType = B73)

This process results in CGMA document with type = B19, and publication of **initial reference program** (docStatus = A01) finalized at 17:15h CE(S)T.

After the CGMA platform provides the initial results based on one of the following options:

- the responsible TSO(s) will submit pole split and loss calculation document (PSLCD) with externally calculated flows and losses on DC links by splitting the DC links into single poles (if applicable) by PSLCD gate closure time (17:28h CE(S)T), or

- if TSO(s) agree on an internal pole splitting and loss calculation, CGMA itself will perform the calculation based on defined pole capacities and loss factors.

The final CGMA document (docStatus = A02) with PSLC results will be provided by the CGMA platform at 17:30h CE(S)T and will create two different types of documents.

The first of the document types is providing the results in “PEVF notation” with type = B29 (PSLC results by using the same business types and the concept of virtual scheduling areas).

The “CGMA notation” of the final results is of the same format of the document, with type = B29 (PSLC results), as the initial results of CGMA for the alignment process, with a slight enhancement in terms of a dedicated business type for balanced DC net flows at the importing end (businessType = B67).

With the combination of businessType (B67 or B68) and the EIC T code of the DC link/pole connectingLine_RegisteredResource.mRID, provided as well in the Boundary Data Set, the information is mapped to the importing (B67) or exporting (B68) end of the DC link/pole.

CGMA process targets multiple time horizons as well, defined by the process.processType (see Table 5).

For IGMs and CGMs validation process, and CGM creation process, the final CGMA results are to be used.

Amongst all the time series descriptive information, there is as well the information of the curveType used to describe the type of curve that is being provided for the Time Series in question. In case of PEVF document, the curveType A02 - “Point” is used (see 10.2.4 for details).

10.2.4 curveType

The TimeSeries class contains the information of the curveType.

The TimeSeries.Period class provides following details describing what the TimeSeries of specific curveType represents:

- timeInterval.Start and timeInterval.End
  All time intervals for the time series in the document must be within the total time interval associated to the MarketDocument class. In case of the PEVF and CGMA documents, they are identical.
- resolution
- PEVF document and CGMA document in PEVF notation: PT1M – one minute resolution
- CGMA document: PT1H - one hour resolution
- Point.position(s) is the relative position of a period within a time interval. It provides all the content for a given time step which is identified by the position. The position always begins at the value “1”. The maximum number of repetitions of the Point class is determined assuming that all variables are expressed as an integer number of resolution units by the formula:

$$\frac{timeInterval.End - timeInterval.Start}{resolution}$$

- The effective number of Intervals depends on the curveType element contents.
- The exact time position within is calculated using the formula:

$$TimePosition = timeInterval.Start + \big(resolution * (position - 1)\big)$$

- with $position$ being the position value of the Point class.

- Point.quantity is the constant power in MW (measurement_Unit.name = MAW) on the time interval.

The curveType used in PEVF document and PEVF notation of CGMA document is Variable Sized Blocks (A03). The curve is made of successive intervals of time (Blocks) of variable duration (size), where the end date and end time of each Block are equal to the start date and start time of the next interval. For the last Block the end date and end time of the last Interval would be equal to timeInterval.End.

PEVF document, and any market schedule that uses the curveType Variable Sized Blocks (A03) with a resolution of 1 minute shall respect the constraint that a change in the block value can only occur based on the bilaterally agreed resolution boundary that has been used in the system operator to system operator matching. As the minimal resolution at this moment is 15min resolution for imbalance settlement, the changes cannot be reported within time period less then 15min.

In case schedules are provided on a 1/4-hour resolution (15-point difference) in a document with PT1M resolution, the values of the 3rd quarter will be used for CGM creation and IGMs and CGM validation, as grid models are provided on a 1-hour resolution. This is per decision made by Regional Group Continental Europe[21].

The curveType used in CGMA document is Point (A02). The curve is made of successive instants of time (Points). It corresponds to a Period where only the interval positions that have data are present within intervalTime. The resolution corresponds to the smallest expected interval between two Points.

10.2.5 Comparing PEVF and CGMA with IGMs

When comparing values with PEVF and CGMA with IGMs it should be considered that:

- There is no sign convention in PEVF and CGMES as all values are positive and there are different properties for in_Domain and out_Domain, which provide flow direction.
- Net Position means the netted sum of electricity exports and imports for each market time unit for a scheduling zone.
- If in_Domain is the TSO, it means an import to the TSO area.
- If out_Domain is the TSO, it means an export from the TSO area.
- For QAR report and QAS portal, the import is represented by a negative value and the export by a positive value.

10.2.6 Mapping for HVDC links

The schedule messages identify objects using Energy Identification Codes (EIC). The linkage between the schedule messages objects and the CIM objects is accomplished by adding the EIC to the CIM objects in the attribute entsoe:IdentifiedObject.energyIdentCodeEic. This attribute exists when there is a link to object in schedule messages.

This interface is only valid for HVDC Links between two scheduling areas. If a link is internal within a scheduling area refer to section 10.4.

Market schedules are defined per HVDC Link. An HVDC Link consists of one or more HVDC Poles where each HVDC Pole may be operated independently.

[21] 58th Plenary Meeting on 29 September 2020.

The HVDC Link schedule is divided per HVDC Pole in the pole splitting and loss calculation (PSLC) process.

In the **CGMA** process, this can be done either internally or externally by a TSO or RSC/RCC. If done externally, the involved TSOs decide how to split the losses. If done internally in the CGMA process, a simple model using parameters from the boundary definition is used, e.g., pole distribution factors and loss parameters in percent of active power transfer. The computed losses are added to the sending side so that the requested power from the receiving side is serviced. If done externally by TSO or RSC/RCC they can benefit from the detailed HVDC model where a loss calculation formula describes how the components in an HVDC Pole contribute to the losses.

The pole split and loss calculation is required as HVDC Link schedules contain the total flow in all HVDC Poles without losses.

The inputs and outputs are:

- Input pre-processing data (PPD) sent by each TSO. PPD contains schedules per HVDC Link and area interchanges. CGMA performs PSLC either internally or by getting the PSLC data from the TSOs, see next bullet.
- Input PSLC data sent by a TSO. The PSLC data contain schedules per HVDC Pole at sending and receiving side as well as the losses (difference between active power at the sending and receiving side). PSLC data are provided only by TSOs connected to an HVDC Link and can be submitted by only one of the connected TSOs (single-side data provision).
- Output is the “final reference program” with area interchanges and HVDC Pole schedules aligned.

For post-market closure time frames, day-ahead and intraday, PSLC is always done externally by the TSO and provided as **PEVF** documents.

The RIMD/RMD document describe area interchange where the subject_domain.mRID defines a collection of HVDC Links, the in_Domain.mRID and out_Domain.mRID describe the scheduling areas, and connectedLine_RegisteredResource.mRID specify the specific link.

The HVDC losses are taken by the sending side, and this is accomplished by a virtual scheduling area in the middle of the HVDC line as explained with the example in Figure 13 (the example is valid for PEVF files and PEVF notation of CGMA final result file, as the VSA are being used).

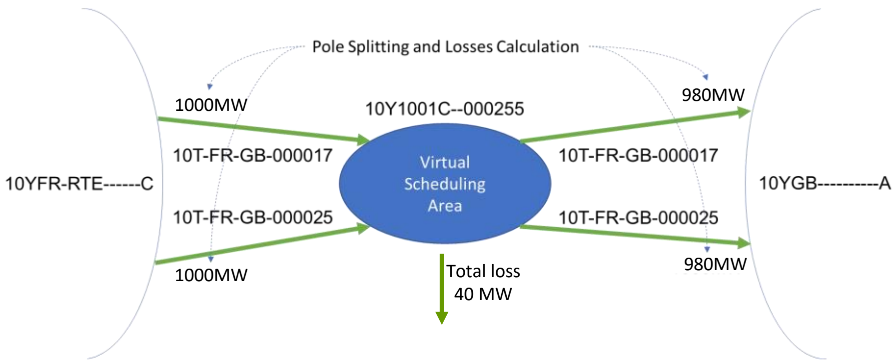


Figure 13 Example Pole Split and Loss Calculation (PSLC)

Figure 13 shows an example HVDC Link with two HVDC Poles (an HVDC Bipole) identified by EIC codes 10T-FRGB-000017 and 10T-FRGB-000025. In the middle of the HVDC Link there is a virtual scheduling area (VSA) cutting the HVDC Poles in two halves. In Figure 13 the HVDC Link loss is 2% of the transferred power and each HVDC Pole transfer 1000MW with 20 MW loss per HVDC Pole.

This example assumes that the receiving TSO requested a transfer of 1960 MW in total, the sending TSO will then have to increase the transfer with 40 MW to 2000 MW in total to reach the requested 1960 MW.

A RIMD/RMD message describing this PSLC contains the following four TimeSeries (schedules):

- Exchange from 10YFR-RTE------C to 10Y1001C—000255 (the VSA) using the HVDC Pole 10T-FRGB-000017.
- Exchange from 10YFR-RTE------C to 10Y1001C—000255 (the VSA) using the HVDC Pole 10T-FRGB-000025.
- Exchange from 10Y1001C------000255 (the VSA) to 10YGB----------A using the HVDC Pole 10T-FRGB-000017.
- Exchange from 10Y1001C------000255 (the VSA) to 10YGB----------A using the HVDC Pole 10T-FRGB-000025.

One cim:Line represents each HVDC Pole in the RIMD/RMD messages above. The sides of the HVDC Pole is determined by the scheduling area EIC code that matches the cim:ControlArea with the in_Domain.mRID and out_Domain.mRID at the two sides.

A method that could be used to find the network objects to update from the schedule is described in terms of the network objects and the schedule message. The below method is described to show that sufficient data for it is present in the CGMES standard.

- Each HVDC Pole is described by four TimeSeries in the schedule message, two for TSO1 to VSA and two for VSA to TSO2.
- The connectingLine_RegisteredResource.mRID EIC code is the same as the EIC code of the cim:Line-s and cim:ConnectivityNode-s contained in the cim:Line-s representing the HVDC poles/link in the Boundary Data Set.
- The out_Domain.mRID and in_Domain.mRID in a TimeSeries refer to one of the following pair of EIC codes:
- EIC_Y code of cim:ControlArea of TSO1 and EIC_Y code of the VSA.
- EIC_Y code of cim:ControlArea of TSO2 and EIC_Y code of the VSA.
- The two TimeSeries that refer to the same VSA describe the flow from one TSO to the other.
- The EIC_Y code in the out_Domain.mRID define the area sending power and the EIC_Y code in the in_Domain.mRID define the area receiving power, the cases are:
- Export from TSO1 to TSO2:
- One TimeSeries have the out_Domain.mRID referring to the TSO1 cim:ControlArea and the in_Domain.mRID referring to the VSA.
- The other TimeSeries have the out_Domain.mRID referring to the VSA and the in_Domain.mRID referring to the TSO2 cim:ControlArea.
- Export from TSO2 to TSO1:
- One TimeSeries have the out_Domain.mRID referring to the TSO2 cim:ControlArea and the in_Domain.mRID referring to the VSA.
- The other TimeSeries have the out_Domain.mRID referring to the VSA and the in_Domain.mRID referring to the TSO1 cim:ControlArea.
- The cim:Line contains two boundary points each for each HVDC Pole. The cim:DCConverterUnit at each side in the HVDC Pole is found using the EIC T code from the

connectingLine_RegisteredResource.mRID attribute in the TimeSeries.

- The side of the HVDC Pole where the schedule is feeding power into the pole gives the active power values for the converter (cim:ACDCConverter.p) and the cim:EquivalentInjection. The power flow at the other side is computed by the power flow calculation.
- The AC IGM and the DC IGM (if exists) has a branch (e.g. cim:ACLineSegment) connecting it to the boundary point.
- The branch in the AC IGMs has a cim:Terminal:
- that connects to the boundary point in a cim:Line
- that has a cim:TieFlow that links to the cim:ControlArea that has the EIC code referring to the in_domain or out_domain. The cim:ControlArea gives the flow direction depending on the matching out_Domain.mRID or in_Domain.mRID as described above.
- The branch in the DC IGM has a cim:Terminal that connects to the boundary point. The cim:ACDCConverter has a reference cim:ACDCConverter.PccTerminal that is the cim:Terminal connecting to a boundary point.
- The boundary point has an cim:EquivalentInjection both in the DC IGM and the AC IGM.
- The power flow inputs (the SSH profile values) in cim:EquivalentInjection-s and the cim:ACDCConverter are updated with the active power flow from the schedule. Operating mode and active power control mode of the converters are also updated depending on the applied changes.

10.3 Concept of Virtual Scheduling Areas for HVDCs schedules

The concept of Virtual Scheduling Areas for HVDCs schedules is used in PEVF files and in the PEVF notation of CGMA final results.

An external HVDC Link is modelled consisting of one or more HVDC Poles where each HVDC Pole is represented as a cim:Line. Due the lack of explicit modelling of the poles in CGMES v2.4, the cim:Line-s representing the HVDC Poles link to market data by using the EIC identification. After pole splitting of the HVDC Link schedules it is then possible to assign the pole split schedule values to the EIs in the AC IGMs connecting the HVDC Link.

An internal HVDC Link, is modelled as a DC IGM with both ends of the HVDC Link connecting to the same AC IGM describing the TSO network. Note that the cim:Line-s describing the HVDC Poles must be in the BDS.

The market schedule concept introduces scheduling area also denoted as “virtual scheduling area” (VSA) which covers the losses of the HVDC Link. The market information from PEVF/CGMA messages that matches network data is shown in Figure 14.

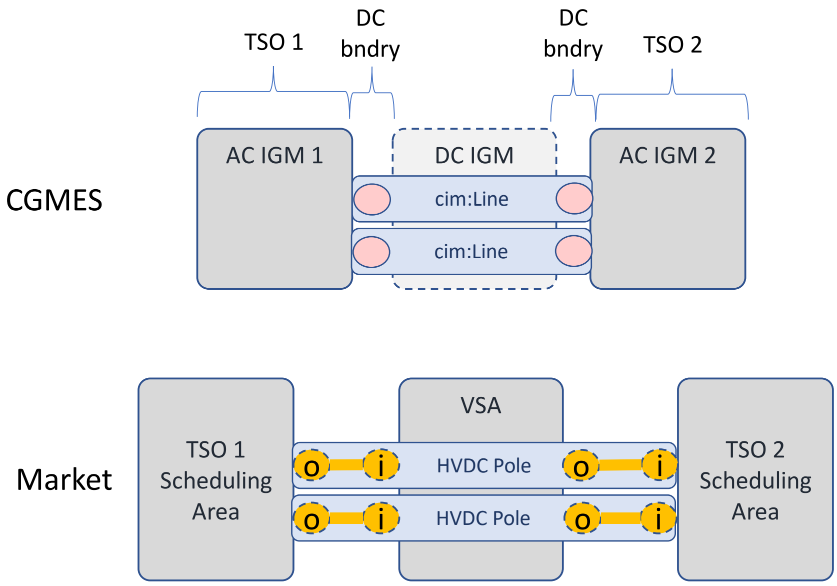


Figure 14 Virtual Scheduling Area (VSA) Market DC Interface

A TSO Scheduling Area in the market message corresponds to the cim:ControlArea in the AC IGM. The VSA corresponds to the cim:ControlArea in the DC IGM.

As for the injection models and representation by EI connected to boundary points the DC IGM is not present, the VSA has no mapping for these models. The mapping is done via boundary points that also have the EIC T code of the HVDC Pole. If there is a mismatch between the cim:EquivalentInjection.p active power flow and the schedule values for an AC IGM used with the injection model, the cim:EquivalentInjection.p values are to be directly updated from the HVDC Pole schedule values and cim:EquivalentInjection.q values recalculated maintaining the original power factor.

Market messages describe the power exchange between two scheduling areas as a time series CIM object. A time series CIM object describes the import and export between two scheduling areas. The exporting area is denoted as “out_domain” and the importing area - “in_domain”. In Figure 14 a time series is symbolized with a thick orange line with two circles at each end. The circles contain the letters “i” for “in_domain” and “o” for “out_domain”. As Figure 14 shows an HVDC Bipole eight time series CIM objects are needed to describe the exchange between TSO 1, VSA and TSO 2. As the time series only allows positive values two time series are needed to describe the exchange between two areas. The time series per HVDC Pole are:

- TSO1 -> VSA
- VSA -> TSO1
- TSO2 -> VSA
- VSA -> TSO2

An HVDC Pole in the market message corresponds to a cim:Line in CGMES and the two cim:DCConverterUnit-s, all have the EIC T code of the HVDC Pole. The boundary points also have the EIC T code of the HVDC Pole.

If there is a mismatch between the cim:EquivalentInjection.p active power flow and the schedule values for an AC IGM used with a detailed DC IGM, the cim:EquivalentInjection.p values cannot be directly updated from the HVDC Pole schedule values as the losses may not be properly represented. A power flow calculation will compute the HVDC Pole losses by using the loss formula from IEC TS 61970-600:2017 and the loss parameters from the DC IGM. The computed losses may differ from the losses used in the HVDC Pole schedules. Hence only the schedule values for the sending side shall be used to update the cim:EquivalentInjection.p values at the rectifier side. The cim:EquivalentInjection.p values at the inverter side are computed by subtracting the computed losses from the schedule values at the sending side.

10.4 Schedules for HVDC Links embedded in an IGM from the same TSO (internal HVDC)

TSO internal HVDC Links transfer power within the TSO but may redistribute the power exchange over tie lines to other TSOs. In the case the HVDC Link is close to the border a single or a group of tie lines may carry the power transferred by the HVDC Link as showed at the bottom in Figure 15 and exemplified in section 12.2.4.

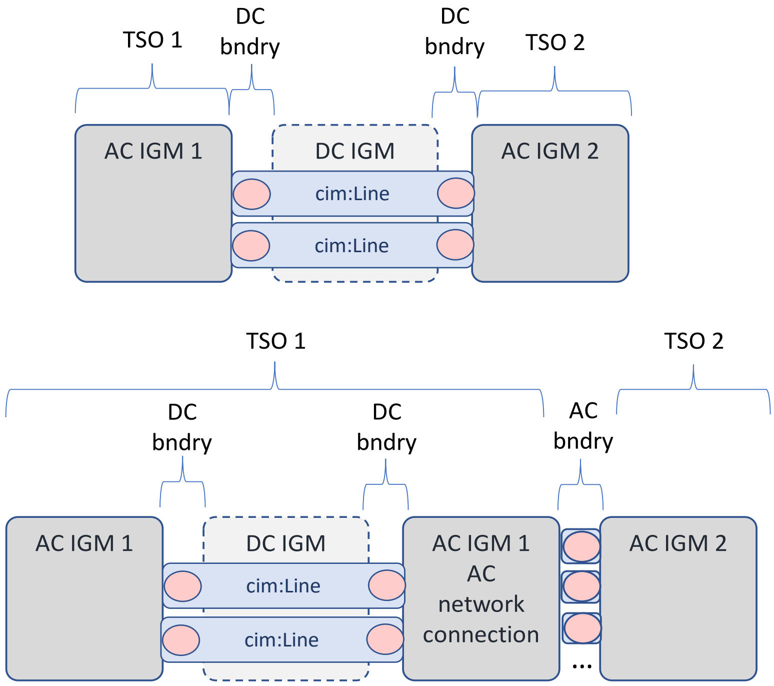


Figure 15 Boundaries for internal and external HVDC Links

Another example is Krigers Flak shown in Figure 16.

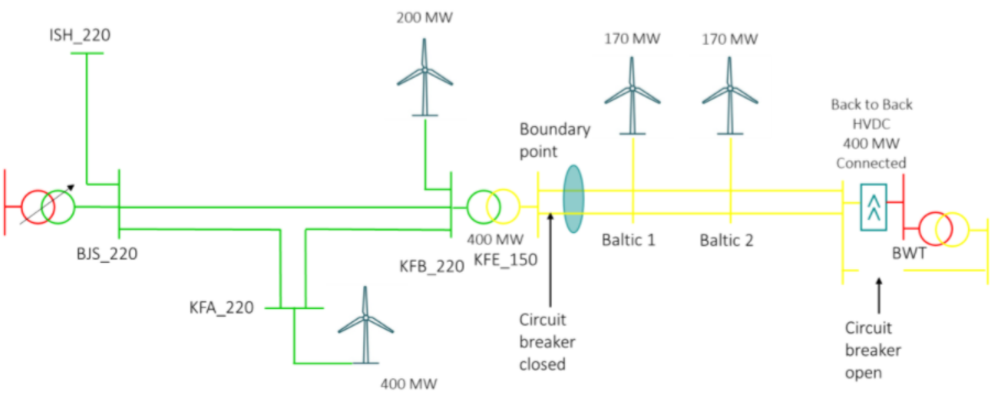


Figure 16 Krigers Flak example

When a HVDC Link is “internal” as shown in the lower part of Figure 15 and Figure 16, the goal is to control the flow the across the AC boundary points with the HVDC Link. Assuming the “AC IGM 1 AC network” Figure 15 has one or two AC transmission lines the flow across the AC boundary equals the flow into the AC transmission lines from the HVDC Link minus the losses in the AC transmission lines. As the flow across the AC boundary points is controlled it is also scheduled. The schedule values are transferred to the HVDC link by adding the losses in the AC transmission lines which results in a schedule for the HVDC Link. These values are used to set the cim:EquivalentInjection injection values in the SSH CIMXML file, which will force the power flow across the AC boundary to be close to the original AC boundary schedule.

In case the remote AC IGM is missing in the CGM there will just be an cim:EquivalentInjection at the boundary without a tie line into the remote IGM. When the active power balance is set up for this CGM it may result in scaling of the cim:EquivalentInjection values, which is not desired as they are held fixed by the HVDC Link. In CGMES v2.4, this is avoided by declaring the TN as a HVDC boundary by setting its cim:IdentifiedObject.description to “HVDC”. In CGMES v3, there is an attribute BoundaryPoint.isDirectCurrent which clearly identifies that the boundary point is a boundary of a HVDC link.

The situation in Krigers Flak is more complex. The goal is again to keep the flow across the “Boundary point” in Figure 16 fixed at scheduled values. In addition to the losses in the AC transmission lines there is wind power production coming from the wind parks “Baltic 1” and “Baltic 2”. The wind park production is forecasted, and the forecast is added to the transmission losses and the schedule at the “Boundary point” which gives the schedule for the HVDC Link, the “Back to Back HVDC”.

Another issue with Krigers Flak is that the schedule is for the sum flow in the two AC transmission lines rather than the individual lines (it is only possible to schedule the sum). This is solved by having a single cim:Line instead of having one for each cim:ACLineSegment. The two AC boundary points for the two AC transmission lines are then in the single cim:Line as shown in Figure 17.

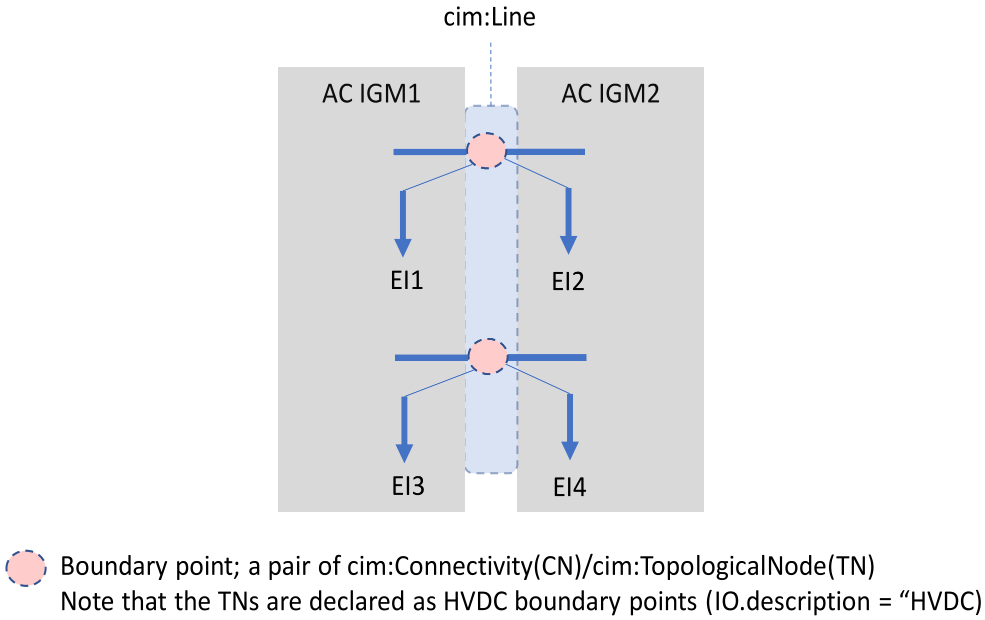


Figure 17 Krigers Flak AC boundary

The cim:Line is linked to objects in the schedule messages via the entsoe:IdentifiedObject.energyIdentCodeEic attribute.

11. Modelling HVDC

11.1 Modelling assumptions and constraints

For details on HVDC modelling alternatives, please refer to ENTSO-E Boundary and reference data exchange application specification.

The CIM version 16 (CIM16) and CGMES v2.4 do not have full support for describing HVDC Links. The following concepts are not described in CIM16: HVDC Links, HVDC Poles and HVDC Bipoles. For this reason, the below described practices are defined.

- Until the issue related to modelling of boundary point in substation is resolved the CGM BP uses representation in which:
- An HVDC interconnection has two boundary points contained in a single cim:Line which represents the modelling of the HVDC pole. The identification of the HVDC Pole is the EIC at the cim:Line;
- An AC interconnection has a single boundary point contained in a single cim:Line.
- Therefore, a DC IGM fits with the boundary data set (BDS) as any other IGM so a DC IGM can be included in a CGM assembly without adjustments to the AC IGMs it connects to.
- A DC IGM where both ends are connected to the same AC IGM are internal to the TSO.
- An internal HVDC link may control the active power flow on an adjacent AC boundary (e.g., Krigers Flak). If this is the case the AC boundary points shall be declared as “HVDC” so it become included in the DC net position instead of the AC net position.
- A DC IGM where the two ends are connected to different AC IGMs is an external HVDC Link connecting two TSOs. One of the TSOs shall take the role of the ModelingAuthority responsible for the HVDC Link and the other will relinquish its ModelingAuthority responsibility to the responsible TSO. Both TSOs have a bilateral interest in the HVDC Link and are supposed to cooperate in creating the DC IGM despite one of them being assigned the modelling responsibility. To support this, a description of the bilateral or shared interest is needed in the information model, for more details refer to Annex A.
- A detailed HVDC model, which by definition models the converters DC equipment, shall be exchanged as a separate DC IGM per HVDC Link. Each DC IGM is defined by a separate cim:ModelingAuthoritySet (MAS).
- A DC IGM shall have a cim:ControlArea with an EIC that matches with the Virtual Scheduling Area (VSA) representing the HVDC Link losses. Note that this is the sum of the losses for the HVDC Poles in the HVDC Link.
- The assembly of an AC IGM with a DC IGM is called an Assembled Grid Model (AGM) rather than a CGM.
- The cim:ControlArea in a DC IGM shall have the type set to Forecast. This is an identification of a VSA and is a temporary solution.
- An AC IGM may have additional cim:ControlAreas with the type set to Forecast. If this is the case the IGM shall not be taken as a DC IGM as the cim:ControlArea of type Interchange rules.
- An HVDC Pole always operate within a power network which means that it is meaningless to solve a power flow for a DC IGM alone and it shall always be used in a CGM where it is assembled with the AC IGMs.

- An HVDC Link can be built as a Current Source Converter (CSC) or a Voltage Source Converter (VSC). This is determined by the presence of cim:CsConverter and cim:VsConverter instances in the cim:DCConverterUnit.
- A CSC requires filters for removal of harmonics. If the CSC filters are modelled, they shall be included in the AC IGM, not the DC IGM.
- CIM and HVDC modelling concepts defined in IEC HVDC standards require distinguishing between a point of common coupling (PCC) and a PccTerminal. In addition, a boundary point may be located in different places depending on HVDC configuration. Therefore, the statement that a boundary point is located at PCC is no longer valid. However, it is required that the cim:ACDCConverter.PccTerminal is associated (connected) directly with the boundary point related to a branch end of an HVDC Pole. In CIM, branches are represented by a retained cim:Switch (and subclasses), cim:ACLineSegment, cim:SeriesCompensator, and cim:PowerTransformer. A convenient way to find the boundary point at a converter is to use the cim:ACDCConverter.PccTerminal.
- Each HVDC Pole has one PccTerminal at each end where the power flow into the AC network is monitored. The voltage (potential) measurement is normally located on the AC side of the breaker and the current measurement (a current transformer) is located on the converter side of the breaker as shown in examples in Figure 20.
- An HVDC Bipole consists of two HVDC Poles described by a pair of cim:Lines. An HVDC Bipole itself is not described by a specific object so there is no association between an HVDC Bipole and its HVDC Poles. But the relations between them can be found by following other associations, e.g. topology and containment.
- HVDC Bipole shall be modelled with four boundary points and each of the two HVDC Poles are modelled by a cim:Line. Each HVDC Pole in an HVDC Bipole will have its own pair of PccTerminals.
- Control of voltage, reactive or active power flow with tap changers is described by the cim:RegulatingControl class. The tap changer at HVDC converter transformers is normally controlled by the HVDC control system that in CIM is described by the cim:ACDCConverter class and its subclasses. This is implicit modelling of the control which requires that the tap changer at converters' transformers shall not be associated with a cim:RegulatingControl to avoid over specifying the control.
- A 12 pulse CSC shall be represented by a single cim:DCConverterUnit with a single cim:CsConverter, see also section 12.1.1 and Figure 24.

11.2 Containment

This section describes the containment rules for HVDC equipment.

- A converter is located in its own cim:Substation. The reasons for this are:
- Converters are commonly built and organized in a separate converter substation.
- The boundary model does not support a boundary point within a cim:Substation, the boundary point need to be contained in a cim:Line[22].

[22] ENTSO-E amendments to the boundary and reference data fix the issue with having boundary point in a substation. However, there will be a transition period until this is supported by all systems.

- A converter substation includes:
- One or more cim:DCConverterUnit-s and a cim:DCConverterUnit must be contained by a cim:Substation. Therefore, requiring association end cim:DCConverterUnit.Substation is necessary.
- A cim:DCConverterUnit can contain any AC objects, common objects are
- Subclasses of cim:ACDCConverter (cim:CsConverter or cim:VsConverter) that are both a AC and DC object.
- Subclasses of cim:Switch
- cim:PowerTransformer
- cim:ConnectivityNode and cim:TopologicalNode
- Note that:
- cim:VoltageLevel is not allowed to be contained by a cim:DCConverterUnit.
- AC objects in a cim:DCConverterUnit shall have a reference to cim:BaseVoltage in the boundary.
- In CGMES v2.4 the attribute ACDCConverter.ratedUdc is assumed to be the same for all DC equipment in the cim:DCConverterUnit which means that it is sufficient to locate the cim:CsConverter or cim:VsConverter in the cim:DCConverterUnit to obtain the information on rated DC voltage. The issue of rate DC voltage for DC equipment is fixed in CGMES v3.
- Active and reactive sources as cim:SynchronousMachine-s, cim:StaticVarCompensator-s, shunts and filters shall not be located in the cim:DCConverterUnit, but in a cim:VoltageLevel within the AC IGM.
- In the case filters are included in a fictitious converter substation in the AC IGM they shall be in a cim:VoltageLevel as stipulated by existing containment rules.
- The branches that connect with the boundary follow the containment rules, i.e.
- A cim:ACLineSegment is contained by the boundary cim:Line.
- A cim:Switch is contained by a cim:VoltageLevel or a cim:DCConverterUnit.
- A cim:PowerTransformer is contained by a cim:Substation or a cim:DCConverterUnit.

11.3 HVDC Link control

HVDC Link control is divided in levels that are:

1. HVDC Link control
2. HVDC Bipole control. The two HVDC Poles in the bipole are coordinated at this level and the active power exchange over the two HVDC Poles is controlled.
3. HVDC Pole control. The target is active power transferred over the pole which is controlled as follows:
   a) The converter with the lowest dc voltage determines the dc Voltage, the converter operates in voltage control mode, this is the inverter.
   b) The converter with the highest voltage determines the dc Current according to the formula idc = (vdc[r]-vdc[i])/R, see Figure 20. The rectifier operates in current control mode and the inverter in voltage control mode.
4. HVDC Converter unit control. Input is dc Voltage or dc Current target.

a) In voltage control mode the dc Voltage is controlled by the tap changer and firing/extinction angles. The angle control is fast but has a limited range. Hence the angles are used to track changes and when the limit is reached the tap position is changed. The target firing/extinction angles and tap position are the output.

b) In current control mode the dc Current is controlled by setting the dc Voltage at the sending side and voltage control is used to accomplish this.

5. Bridge control, which given the target angle, generates the ignition pulses to the thyristors or IGBTs.

The upper levels 1 to 3 are the same for CSC and VSC. Figure 18 shows the control levels described above.

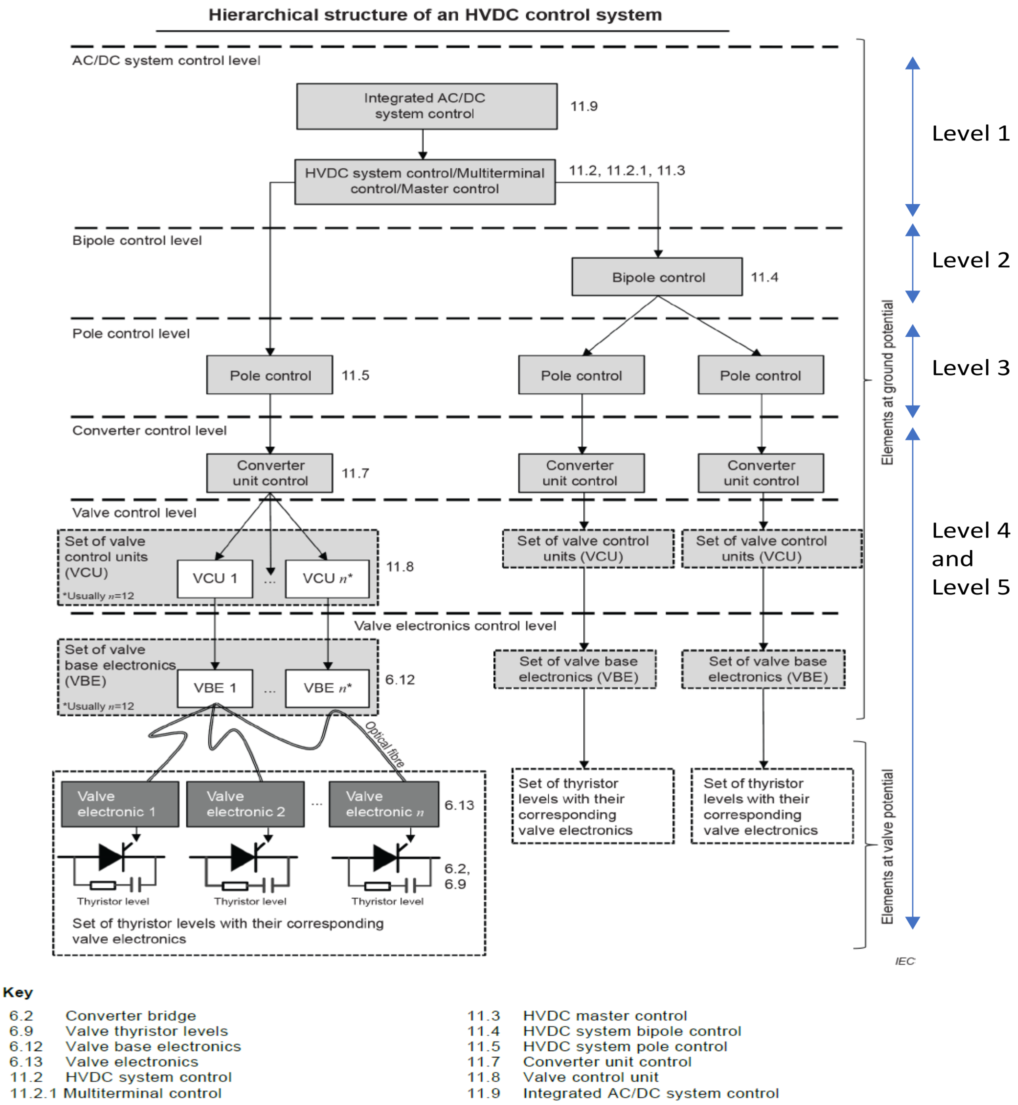


Figure 18 Hierarchical control structure from IEC 60633

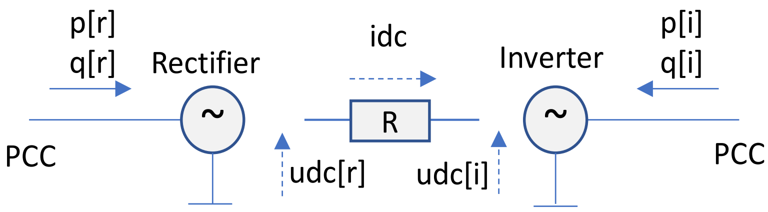
Level 1 in Figure 18 is the HVDC Link scheduling process that determines the flow for individual HVDC Links. For the ID, 1D and 2D processes this data comes from the market, see section 10 Market schedule interface.

Level 2 in Figure 18 is the pole split function, see section 10.3, and gives the HVDC Pole active power flows.

Level 3 in Figure 18 is the individual HVDC Pole control, it takes the active power transfer targets from level 2 as input and generates DC voltage and current targets.

Level 4 in Figure 18 takes the target dc Voltage or dc Current from level 2 as input. For a CSC it generates the tap position and firing/extinction angels as output.

Most power flow calculations only support level 3. Figure 19 show an equivalent model for this.



p[r] = udc[r]*idc
p[i] = -(p[r] – poleLossP)
poleLossP = idleLoss + switchingLoss*|idc| + resitiveLoss* idc^2

Figure 19 Modelling the Converter in power flow

As input the power flow calculation takes the HVDC Pole active power flow from level 2. For a CSC the corresponding reactive power flow is computed. How this is done is outside the scope of this document, but it will somehow consider the discussions in sections 12.1 and 13.1. The number of filters used is also determined. If the converters are described DC voltages, currents and losses are also computed. For VSC the AC voltage, in addition to the active power, is also set as input and the VSC will provide the reactive power to keep the voltage.

11.4 DC Cables

DC cables are connected to the converters (cim:CsConverter or cim:VsConverter) via DC switch gears modelled in CIM by cim:DCDisconnector and cim:DCBreaker. Some DC Substations have DC switch gear that allows for connecting the DC cables to different terminals at the converters allowing for substantial flexibility in DC cable usage.

DC network topology can be described at two levels of detail:

- “Node Breaker” style modelling where all DC switch gear is included in a DC IGM. This requires a DC topology processor that computes the resulting “Bus Branch” model.
- “Bus Branch” style modelling where the connectivity resulting from the DC topology processor is described. The connectivity between converter terminals (cim:ACDCConverterDCTerminal) and DC cable terminals (cim:DCTerminal) are then described by cim:DCTopologicalNodes.

DC IGMs may include an HVDC “Node Breaker” model and must include an HVDC “Bus Branch” model. All tools must be capable of consuming a DC TP CIMXML file and is not required to read the DC Switches and statuses in SSH[23].

[23] However, note that both CGES v2.4 and CGMES v3 have an issue on exchanging statuses of DC switches. This issue is fixed in Network Code profiles.

12. Current source based HVDC interconnection

12.1 CsConverter

12.1.1 CsConverter modelling

A current source converter consumes reactive power depending on active power transfer. When schedules are used to set up a power flow case only the active power is known so the corresponding reactive power consumption must be computed. An approximation is that the reactive power consumption is half of the active power transfer (Q=P/2). Figure 25 gives an example of the dependency between reactive power consumption and active power transfer. It shows that the dependency is nonlinear.

Converters are commonly operated as monopoles or Bipoles. A monopole typically has a single DC cable with ground return, but metallic return is sometimes used. Modern HVDC systems strive to keep ground return current low to minimize environmental impact which favours Bipole solutions with two DC cables. In a Bipole solution the current is circulating which means Idc1 = -Idc2 and that the ground return current is low, see Figure 20.

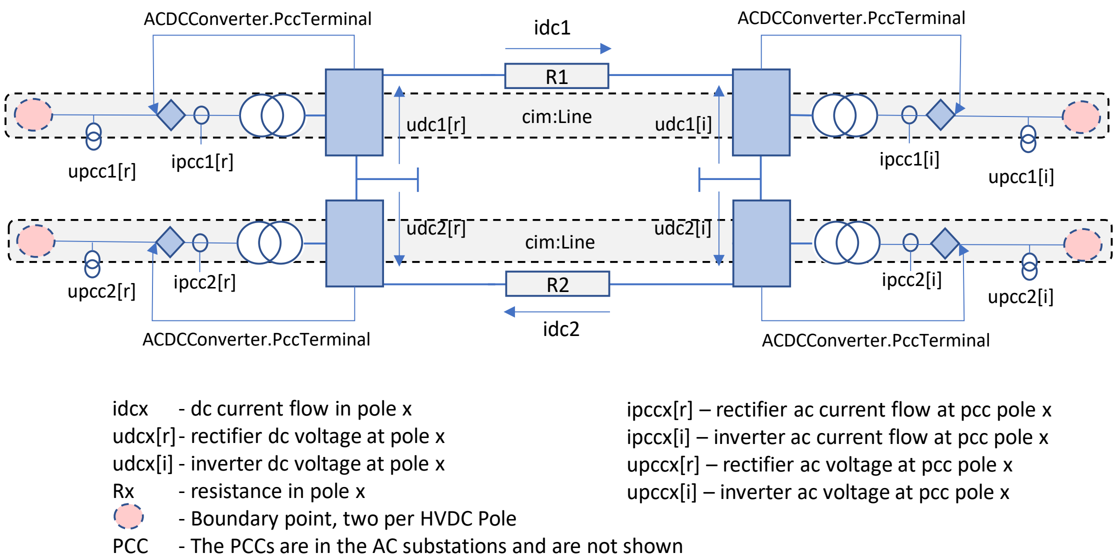


Figure 20 Example HVDC Link Bipole configuration

In an HVDC Bipole as shown in Figure 20 has two HVDC Poles where one operates at positive voltage, the other negative and the midpoint between them is grounded. By keeping the idc1 = -idc2 the losses can be compensated for by slight difference in the voltages udc1[r] and udc2[r]. It is possible to operate the HVDC Poles in a Bipole separately (it happens in fault situations), but if ground currents are minimized this means that the HVDC Poles share the transferred power equally.

To minimize losses a CsConverter is typically operated at maximum dc voltage, which reduces the dc current and the losses. A CsConverter also has a minimum power transfer capability (the attribute cim:ACDCConverter.minP is not available in IEC TS 61970-600:2017 but added in IEC 61970-600:2021). Below this limit the converter must be blocked, the limit is typically 2-10% of the max power capability.

The loss in an HVDC Pole is described by the formula poleLossP = idleLoss + switchingLoss*|idc| + resitiveLoss* idc^2, see also Figure 19. The loss formula is for the converter and excludes the converter transformer and phase reactor. The losses in the converter transformer and phase reactor are computed with the parameters given for them.

As discussed in section 11.3 the control functions depend on each other in a hierarchy where the firing/extinction angles and tap positions are decided at the lower levels. The firing/extinction angles impacts the harmonics generation and reactive power consumption.

Firing/extinction angles are kept in a small range which means that neither the tap position nor the angles are needed in power flow calculations, and it is assumed that the desired dc target voltages can be provided by the lower-level control functions without the need-to-know tap positions nor the angles. However, the parameters for the lower level controls are optional and may be included by an exporting party.

The parameters for the HVDC control of an HVDC Pole are described in cim:CsConverter (CSC) and cim:VsConverter (VSC) classes. Their base class cim:ACDCConverter has a reference, cim:ACDCConverter.PccTerminal, the PccTerminal that is a cim:Terminal where the power flow at each end of an HVDC Pole is monitored. The example in Figure 20 shows the PccTerminal at the cim:Switch cim:Terminal at the boundary point.

A current source converter bridge consists of six valves, see Figure 21.

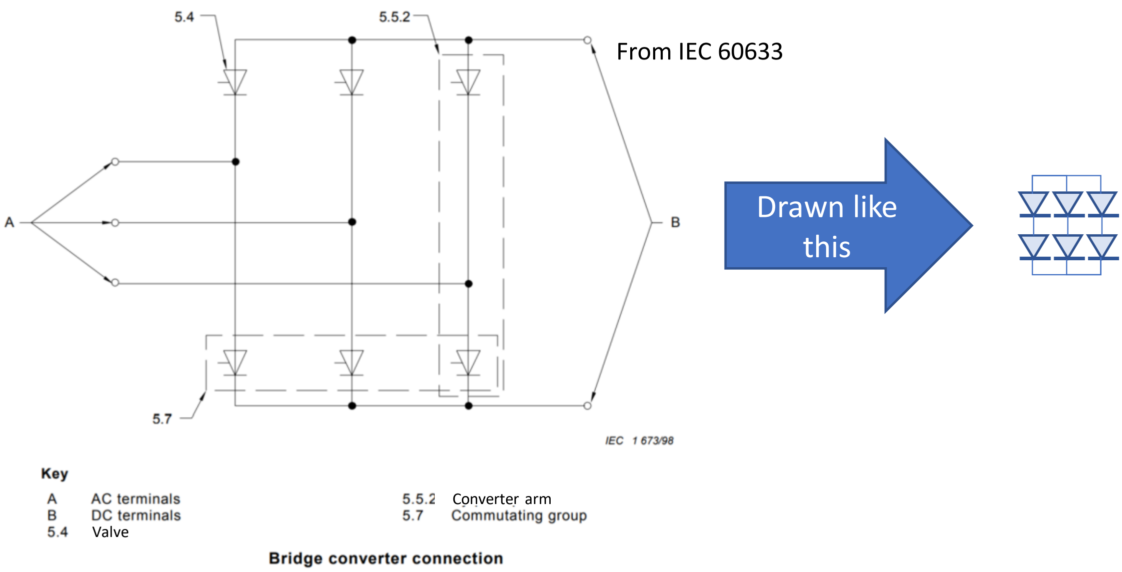
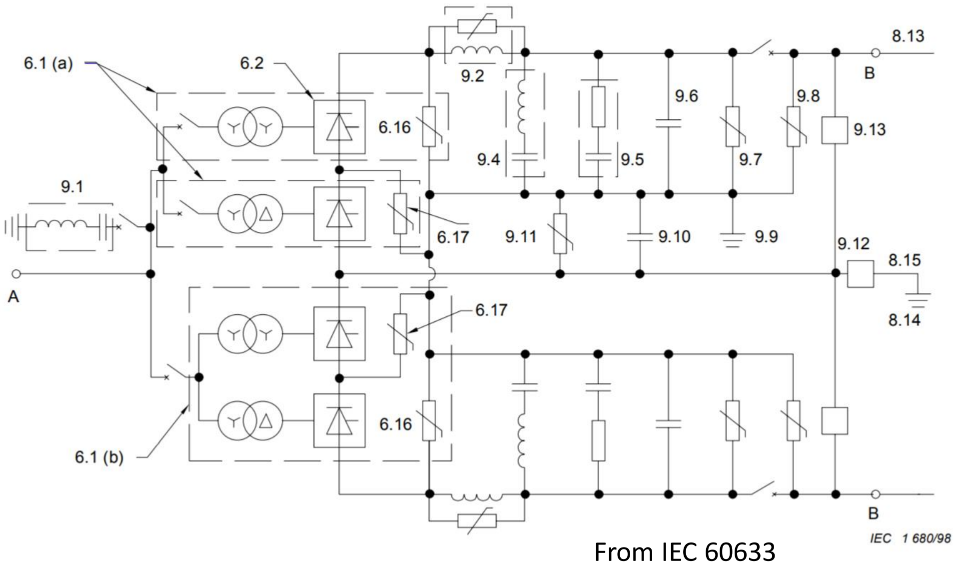


Figure 21 Current source converter bridge

The bridge generates 6 pulses with 60 degrees displacement per AC cycle. The DC voltage generated by a 6-pulse bridge has many harmonics and a way to reduce them is to combine two 6-pulse bridges to generate 12-pulses as shown in Figure 22.



From IEC 60633

Key

A	AC system	9.3	DC reactor arrester
B	DC terminal	9.4	DC filter
6.1 (a)	Converter unit (*p* = 6)	9.5	DC damping circuit
6.1 (b)	Converter unit (*p* = 12)	9.6	DC surge capacitor
6.2	Converter bridge	9.7	DC bus arrester
6.16	Converter unit d.c. bus arrester	9.8	DC line arrester
6.17	Midpoint d.c. bus arrester	9.9	Substation earth
8.13	HVDC transmission line pole	9.10	DC neutral bus surge capacitor
8.14	Earth electrode	9.11	DC neutral bus arrester
8.15	Earth electrode line	9.12	Metallic return transfer breaker (MRTB)
9.1	AC filter	9.13	Earth return transfer breaker (ERTB)
9.2	DC (smoothing) reactor		

Example of an HVDC substation

Figure 22 Example converter substation from IEC 60633

Figure 22 shows two ways to configure the two 6-pulse bridges:

- 6.1(a) with two separate converter units in series, each with one 6-pulse bridge.
- 6.1(b) with one converter unit having two 6-pulse bridges in series.

The lower transformer in 6.1(a) and 6.1(b) has a 30 degrees angle displacement relative to the upper one which results in 12 pulses per AC cycle making the DC voltage smoother and lower the cost for harmonics filtering. Figure 22 shows two two-winding transformers but more common is one three winding transformer. How a monopole with a 6-pulse bridge and ground return can be described with CIM objects is shown in upper part of Figure 23.

Figure 23 shows how a 12-pulse monopole can be built with two 6 pulse bridges in two cim:CsConverter objects.

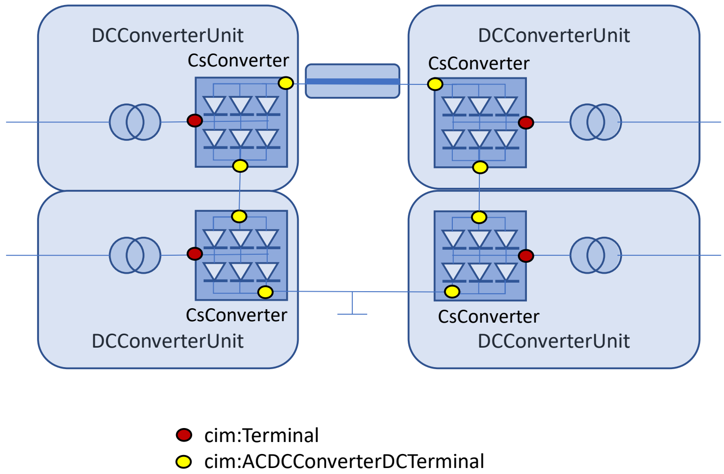


Figure 23 Example a 12-pulse monopole built with two cim:CsConverters which is not allowed

The configuration in Figure 23 corresponds to case 6.1(a) in Figure 22 and needs two cim:CsConverter objects. As the control parameters are also described in the class cim:CsConverter this duplicates the number of control parameters. As the bridges are in series they cannot operate independently so one of the cim:CsConverter control variable sets is superfluous and cannot be used. Therefore, such configuration is not supported by the data exchange.

Another way to describe a 12-pulse monopole with CIM objects is to use a single cim:CsConverter as shown in Figure 24.

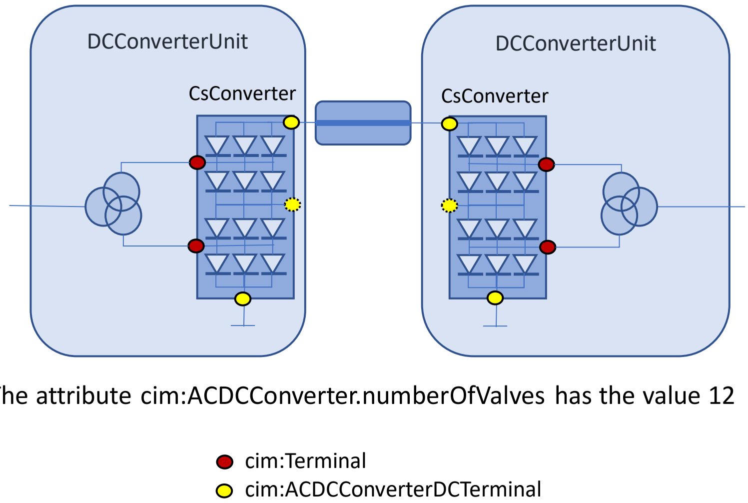


Figure 24 Example of a 12-pulse monopole built with one cim:CsConverter

The configuration in Figure 24 corresponds to case 6.1(b) in Figure 22 and has a single set of control parameters. This is the only configuration allowed for representing a 12-pulse converter described by CIM objects.

Limitations outlined here are due to the cim:ACDCConverter class and its subclasses cim:CsConverter and cim:VsConverter describe the control function as well as the electrical connections with the bridges as shown by the yellow and red dots in Figure 23 and Figure 24.

12.1.2 Location of control objects

Filters may by design be located either in the AC substation (modern HVDC designs), shown in Figure 34, or in the DC Substation (older HVDC designs), shown in Figure 35. As discussed in section 12.1 the filters shall be in the AC IGM while the converters shall be in the DC IGM. As a consequence the voltage control object, e.g. cim:RegulatingControl, and the converter will be in different IGMs (Figure 33). If parameters from the converter are needed by a control function a path between the control object and the converter is needed. A direct reference between the control objects in different IGMs, e.g., the AC and DC IGMs, is not allowed to avoid dependencies between IGMs of different MAS.

For the CSC filter control this is solved by having it described by remedial actions that avoids the need for a filter control object. When filter control objects are added in later versions of CIM, they will reside with the filters in the AC IGM. This is possible because the active power flow from the HVDC Pole is used to determine the number of needed filters.

12.1.3 DC voltage and transformer control

The control of the converter transformer's tap changer is related to the firing and extinction angles of the converter. As these angles reach their limits (small range around 15 degrees) the tap is adjusted, which brings the angles back into the middle of their ranges, see Figure 25.

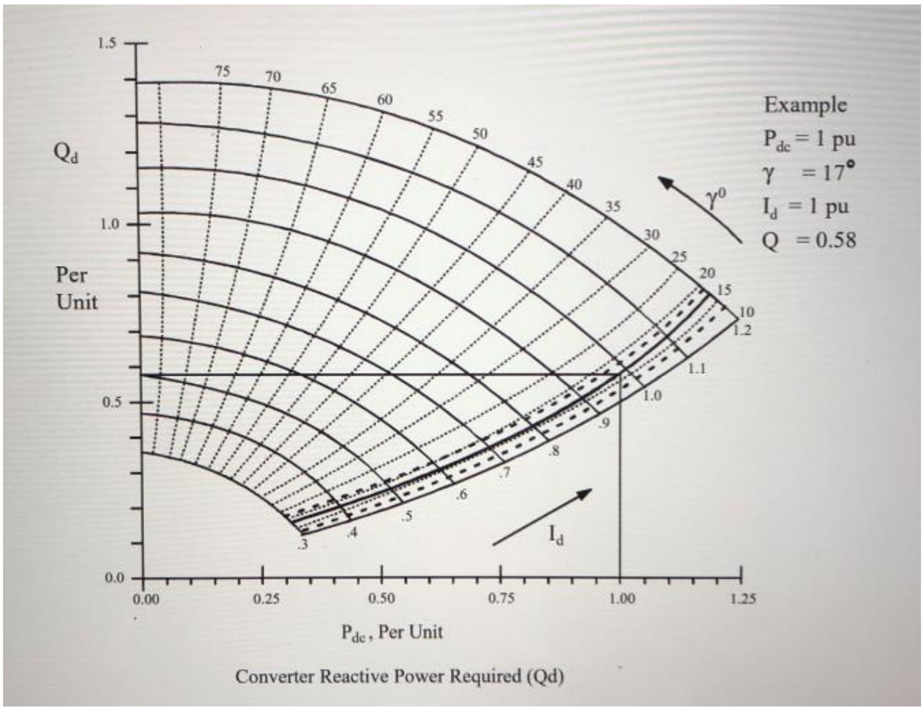


Figure 25 Reactive power consumption as function of transferred DC power

Figure 25 [10] shows an example how reactive power consumption by a CSC varies with active power transfer and firing angle. Due to its special function, the tap changer control of the converter transformer is fundamentally different from the voltage control function described by cim:RegulatingControl.

For power flow calculation this level of detail is not used and the discussion in this section does not need to be considered for power flow calculation, but for dynamics studies the tap position and angles are needed.

The power transformer and the tap changer in a cim:DCConverterUnit has no association with the converter that control the tap changer. To resemble how all other controls in CIM are related with their controlled object an association that links the tap changer, and the CSC is needed but this requires CIM/CGMES changes which is not possible in CGMES v2.4. Tap changer and angle control are not included, e.g., in the power flow calculations, this missing association cause no harm.

12.1.4 HVDC harmonics filtering, reactive compensation, and voltage control

Harmonics appear at specific multiples of the base frequency, e.g., 11, 13, 21, 23, etc. The current caused by the harmonics at the multiples depend on active power transfer. The higher harmonics disturbance the more filters are needed. The filters also provide reactive power that compensate the reactive power consumption by the converter. Filters can be designed to remove all harmonics or be dedicated to specific harmonics multiples. Filter design also impacts the amount of reactive power generated. This must be considered in contingency studies so the power flow calculation can respond to contingencies by proper use of filters and shunts, i.e.

- At the level of harmonics disturbance (a function of the transferred active power) determine which filters to use. The remaining filters are available for voltage control.
- Use the filters not used for harmonics filtering or other available reactive power sources to maintain the voltage.

According to section 11.2 the detailed model of the converters is in their own substation that is connected to the AC substation. With the filters in a

- Converter substation, the converter substation shall be split as described in section 12.2.3, see example in Figure 36.
- AC substation no action is needed as the filters are already in an AC Substation, see example in Figure 34.

The filters used for harmonics are determined based on the active power flow. Depending on filter design they will also compensate the converter reactive power consumption. The converter design determines at what multiples harmonics appear.

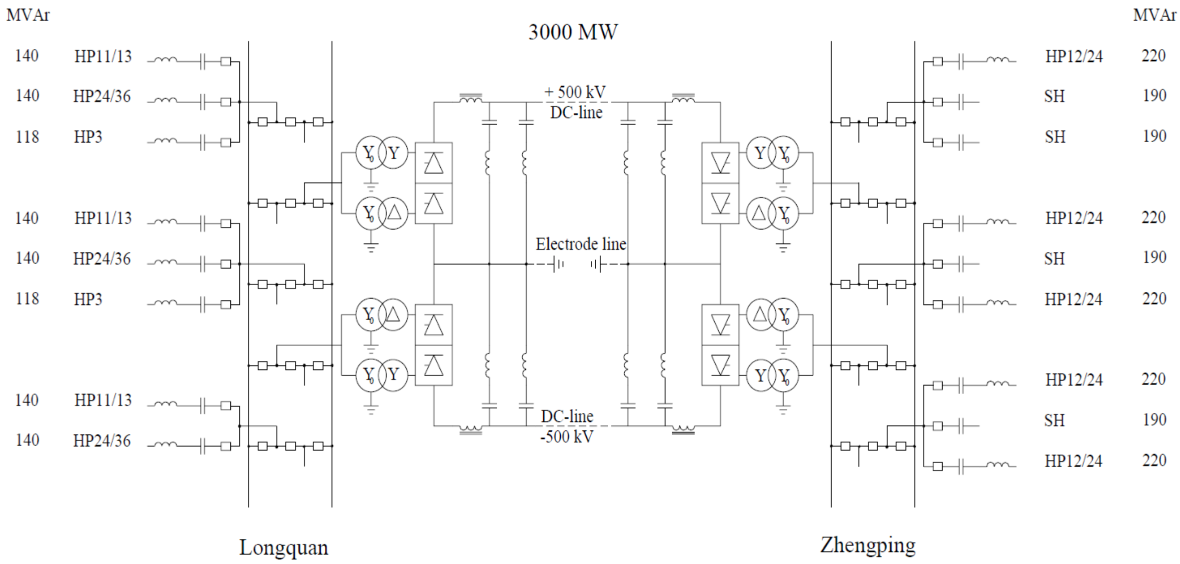


Figure 26 Example filter configuration from Three Gorges China

Figure 26 shows a 12-pulse converter Bipole example that can be flexibly connected to the filters and shunts via a bus bar system at each side. The very left and right columns show the reactive power generated by a filter when connected and next column to the middle show the harmonics multiples taken care of by the filter, e.g., HP11/13 take care of the multiples 11th and 13th. There are several filters tuned for the same harmonics that are connected based on need. The reason why the substation is built with this configuration options is to support fast recovery from component failures. Normally all equipment needed is connected and the substation is not split into two buses operated separately, but in a contingency the substations may be split.

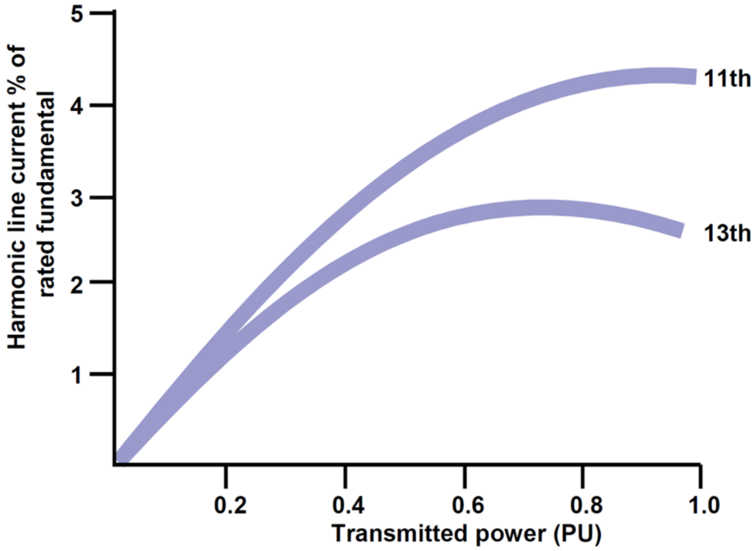


Figure 27 Example of 11th and 13th harmonics multiples as function of active power transfer

Figure 27 shows how the harmonics current increase with increased active power transfer and that the dependency is nonlinear, other examples show that the curves may have quite different shapes. As the harmonics depends on active power transfer the filter control function takes the active power transfer as input it gives the needed filters as output. With this function it is possible to simulate active power flow changes, e.g., due to remedial actions or contingencies.

The thresholds for connection or disconnecting filters are set by a quality index for acceptable level of harmonics currents. The harmonics generation, filter design and control of the filters is highly dependent on the installation, and it is difficult to come up with a general analytical expression for control of the filters. A commonly used solution is instead to describe the filter control by a table where the activation and deactivation of filters is a function of active power transfer. To implement this in CIM will need new CIM classes that describe tabular functions. The filter control function will also need new CIM classes that manage connection and disconnection of filters using the result from the look up in the tabular function. Figure 28 shows an example a tabular filter control function.

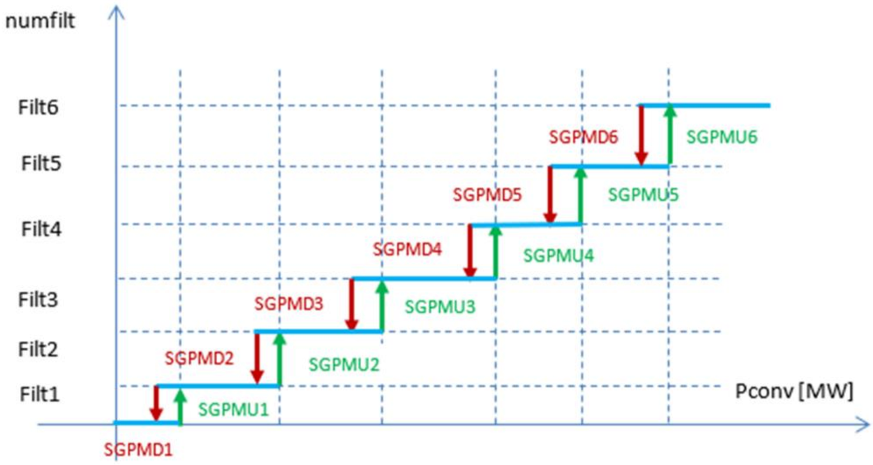


Figure 28 Example filter control function

To avoid extensive switching of the filters, hysteresis is needed so that the switch off threshold is lower than the switch on threshold. The red arrows in Figure 28 show the switch off thresholds and the green the switch on thresholds.

It is not possible to extend CGMES v2.4 with new data for filter control. A work around for remedial actions is to include the behaviour of the filters in the remedial action itself which is the solution used. Remedial actions are described in the CSA specification and for this reason remedial actions are not described here.

12.2 CSC Modelling Use Cases

12.2.1 Example CsConverter monopole case with shunts in AC Substation

This section gives an example of a monopolar HVDC Link including HVDC with a CGM including the AC IGMs at each side of the DC IGM.

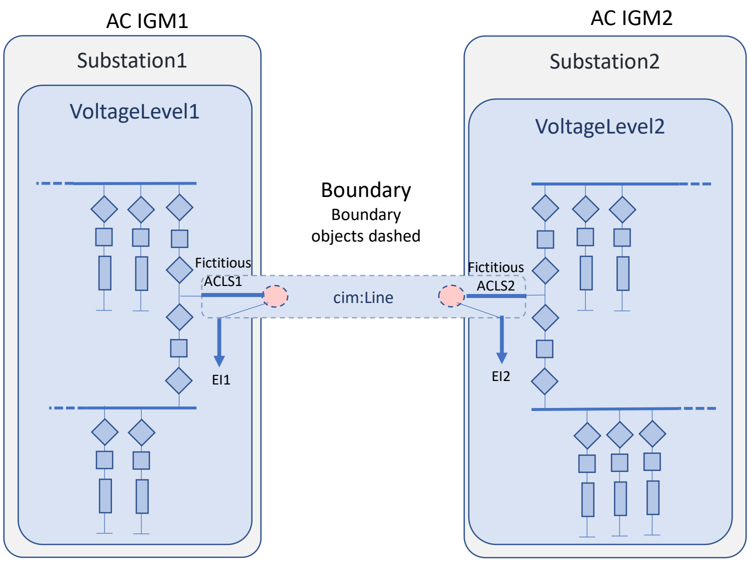


Figure 29 Example of simplified HVDC boundary using injections

Figure 29 shows two AC IGMs connecting to the boundary points at each side of the cim:Line. IEC 61970-301:2020 figure 38 is like Figure 29 and provides the same information. In the example each AC IGM has a fictious cim:ACLineSegment (ACLS1 and ACLS2) connecting to the boundary point and one cim:EquivalentInjection (EI1 and EI2) representing the power flow into the HVDC Pole. ACLS1 and ACLS2 are fictious and introduced to have the required branch connecting to the boundary point.

If there is a cable between the AC substation and the converter the cim:ACLineSegment is not fictitious but real. A fictitious cim:ACLineSegment shall have a small series reactance greater than zero compliant with the QoCDC rule ACLineSegmentX.

If a real breaker or disconnector connects to the boundary it should be used instead of the fictitious cim:ACLineSegment. The reason that CIM models shall, if possible, stay as close as possible to how the power system is built rather than rely on fictitious models.

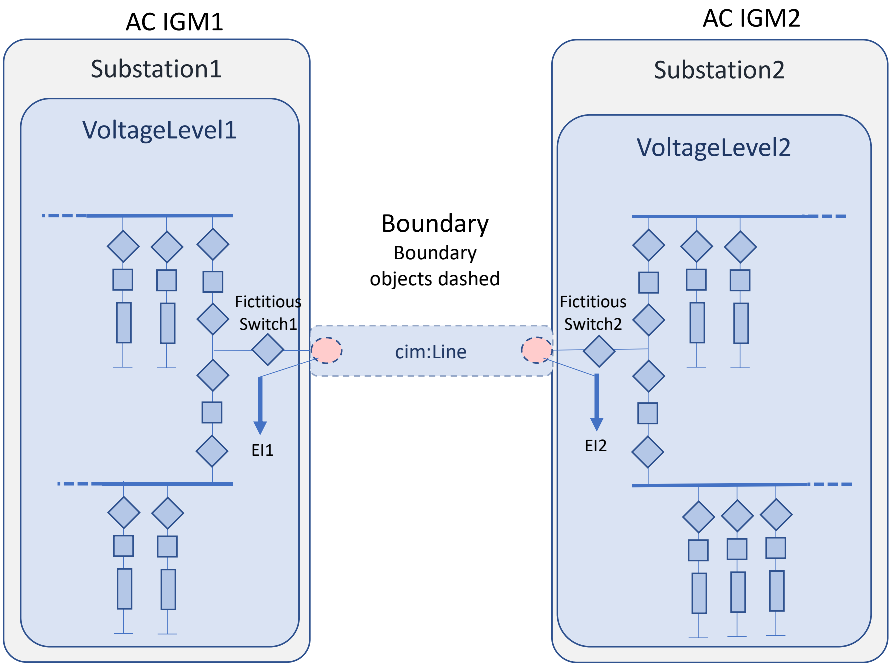


Figure 30 Example of simplified HVDC boundary using injections and fictitious Switches

If ACLS1 and ACLS2 in Figure 29 are replaced by fictious (or real) cim:Switch-es the diagram will instead look as shown in Figure 30.

The active power flow at the two sides shall have different signs and differ no more than the losses in the HVDC Pole. For validation purposes the losses can be assumed to be less than x% of the power flow where the x value will be determined in a revised version of QoCDC. A voltage source converter may not transfer any active power. In this case both sides will consume active power due to the losses which means they both acts as rectifiers.

An example of a detailed DC IGM, a monopole HVDC link with one HVDC Pole and ground return is shown in Figure 31. It shows how the converters (cim:CsConverter or cim:VsConverter), at the two sides of the HVDC Pole are connected via a disconnector to the AC system. The cim:Line with the boundary points is in the dashed box in the background. The cim:ACDCConverter.PccTerminal shall refer to the PccTerminal at the boundary side of the disconnector. As a branch is anyway needed to connect with the boundary point it is advised to include any existing cim:Switch in the model, otherwise a fictitious branch, e.g. a cim:SeriesCompensator or retained cim:Switch is required. The cim:EquivalentInjection-s EI1 and EI2 represent the power flow into the AC systems and as the PccTerminal is also located at the boundary point it is easy to find the scheduled active power in cim:EquivalentInjection-s (the cim:EquivalentInjection.p attribute). cim:EquivalentInjection is contained in the cim:Line.

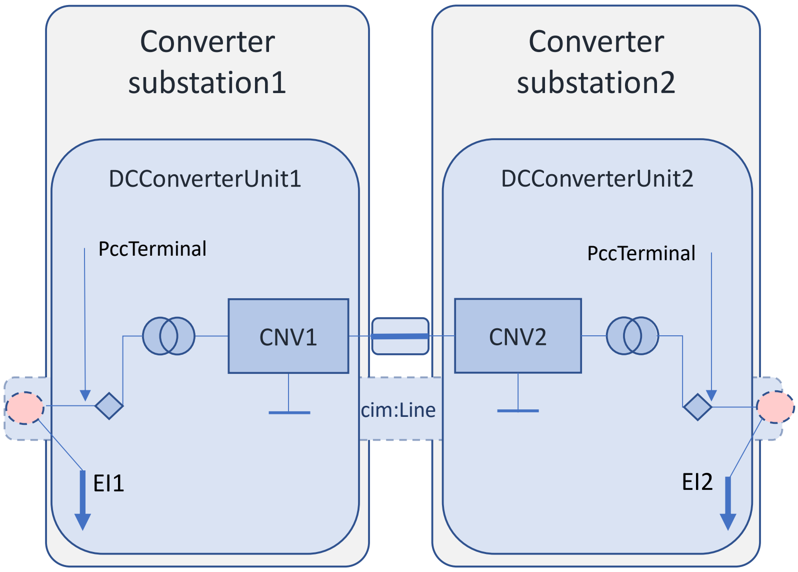


Figure 31 Example of a detailed monopole DC IGM

The EI active power injection values shall have opposite signs and differ no more than the losses in the HVDC Pole. A voltage source converter may not transfer any active power and if so, both sides of the HVDC Pole will consume active power due to the losses. A back to back system has the same interface with the AC system as shown in Figure 31 with the exception that the HVDC cable between the converters are excluded and the converters are directly connected, an example figure for this case is not included in this document.

An example case with a detailed DC IGM assembled with one AC IGM is shown in Figure 32. The use case in this figure is useful when the detailed voltage control of the remote end (at the right side) is of no interest. It is then sufficient to assume that the active and reactive power exchange with the remote AC IGM is described by the cim:EquivalentInjection, EI2 in Figure 32, and the remote AC IGM is not needed.

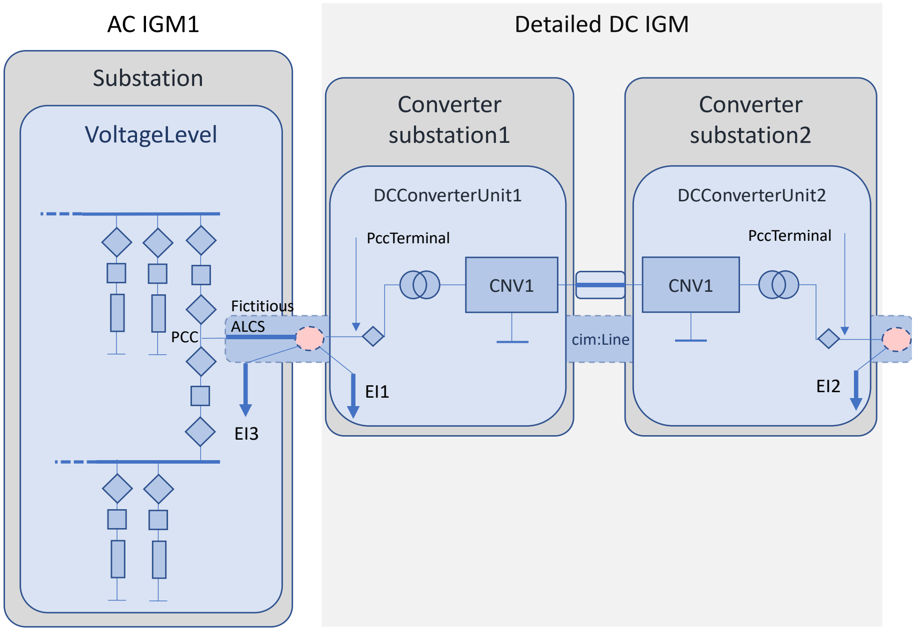


Figure 32 Example with assembly of one AC and one DC IGM

Figure 32 shows how one AC IGM1 connects with a DC IGM. The left side of the boundary has two cim:EquivalentInjection-s EI1 and EI3 that shall be equal with opposite signs (EI1.p + EI3.p = 0). If they are different this means an imbalance between the solutions for the AC IGM and the DC IGM which needs correction. The active power injection values are originally from market or TSO schedules and if they differ the schedules may not have been aligned as described in the CGMA document [10]. The right side has a cim:EquivalentInjection EI2 that represents the power flow into the absent AC IGM. The converter control variables in the SSH CIMXML file shall agree with the injection values at EI3/EI1 and with EI2 including the losses.

The last example is the case where a DC IGM is connected at both sides as shown in Figure 33.

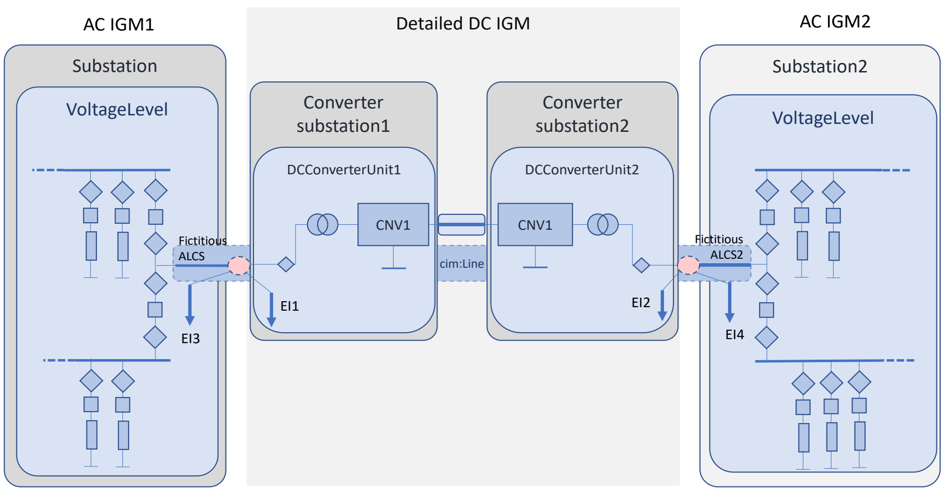


Figure 33 DC IGM connected at both sides

In Figure 33 the power flow through the DC link is determined by the control variable specified in the SSH CIMXML file for the converters as well as the initial EI injection values from the IGMs.

If they are different this means an imbalance between the solutions for the AC IGMs and the DC IGM which needs correction. After solving power flow for the CGM or AGM the injections EI1, EI2, EI3, EI4 and converter control variables are updated with the result and shall agree with each other. A new SSH file for each IGM is created replacing the original.

Note that converter substations in Figure 32 and Figure 33 do not have a cim:VoltageLevel and that the shunts are located in a cim:VoltageLevel within the AC substation according to modern converter substation designs. This means that AC equipment within a cim:DCConverterUnit (e.g. the cim:Disconnector and the two cim:PowerTransformers in the figures) need a reference to a cim:BaseVoltage, which is preferably defined in the equipment boundary file. Older converter substation designs may have the shunts in the converter substation, this case is further discussed below.

12.2.2 Example CsConverter bipole case with shunts in AC Substation

This section gives an example of an HVDC Bipole showing the AGM in Figure 34.

Figure 34 shows how the two HVDC Poles in the HVDC Link are connected in the AC Substations, a common way to build modern HVDC Links. Forcing a single boundary point for the Bipole is not possible due to the substation design (an HVDC Bipole shall not have a single boundary point anyway). Instead, two boundary points per side and HVDC Pole is needed.

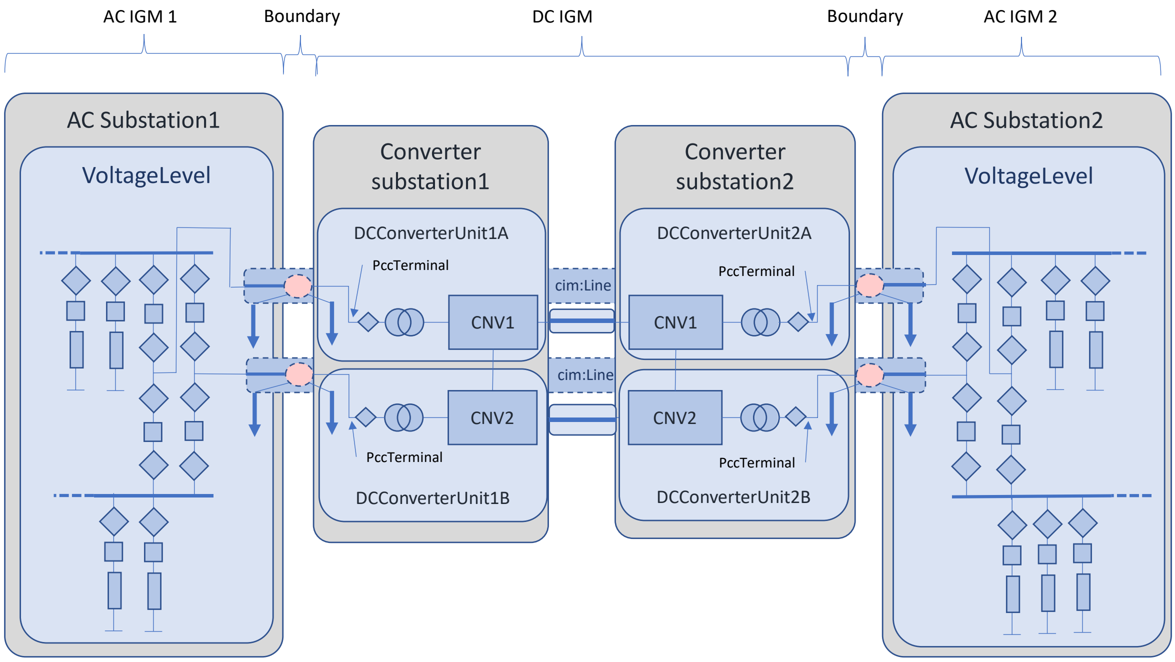


Figure 34 Bipole from example in Figure 20 with added boundary

Figure 34 shows how the two HVDC Poles are connected to the AC Substations with their boundary points and the filters located at two different bus bars in the AC substation. The PccTerminal-s are located at the cim:Terminal at the boundary point side of the cim:Switch for each HVDC Pole. There are HVDC Links where the substations in the AC IGMs are split in two, e.g., Fenno-Skan 1&2.

IEC 61970-301:2020 has a figure 38 showing the case where the HVDC Bipole has a common boundary for the two HVDC Poles, this is not correct. The two boundary points at each of the HVDC Pole has its own cim:Line, which means there is a one to one correspondence with an HVDC Pole and a cim:Line. It is impossible to have a common boundary point for the two HVDC Poles as they are separately connected via separate bays to the bus bars in the AC Substation.

This configuration also has the advantage that the shunts and filters are available without the DC IGM and can be used for realistic voltage control.

12.2.3 Example CsConverter bipole with filters in DC Substation

An example of an HVDC Link with two bipoles connected to the AC substation with two separate cables is shown in Figure 35, only one half of the HVDC Poles are shown.

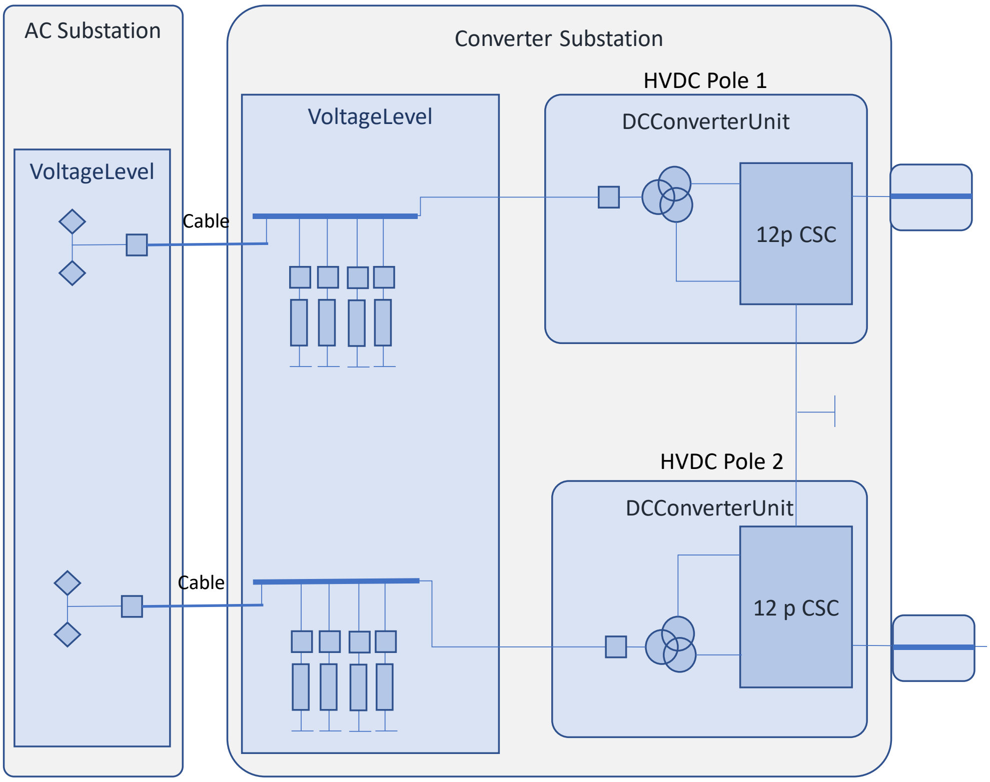


Figure 35 Example Bipole with shunts in DC substation

Figure 35 shows the HVDC Link with shunts and filters in the converter substation which may be the case for older HVDC Links. The HVDC Poles are 12 pulse converters, which means they have two AC connections, see also section 12.1.1. There are two possible boundary locations in Figure 35.

- Between the cim:VoltageLevel in the converter substation and the cim:DCConverterUnit. In this case the boundary is located at the converters in the HVDC Poles.
- Between the AC substation and the converter substation. If the HVDC Poles in a bipole has a common connection with the AC Substation this location cannot be used as a boundary, but this is not the case in Figure 35 so this location is possible. But the location is less desirable as voltage control behaviour is inaccurately modelled.

In the first case the converter substation must be split into one fictitious substation with the filters and the converter substation with the remaining cim:DCConverterUnit-s as shown in Figure 36.

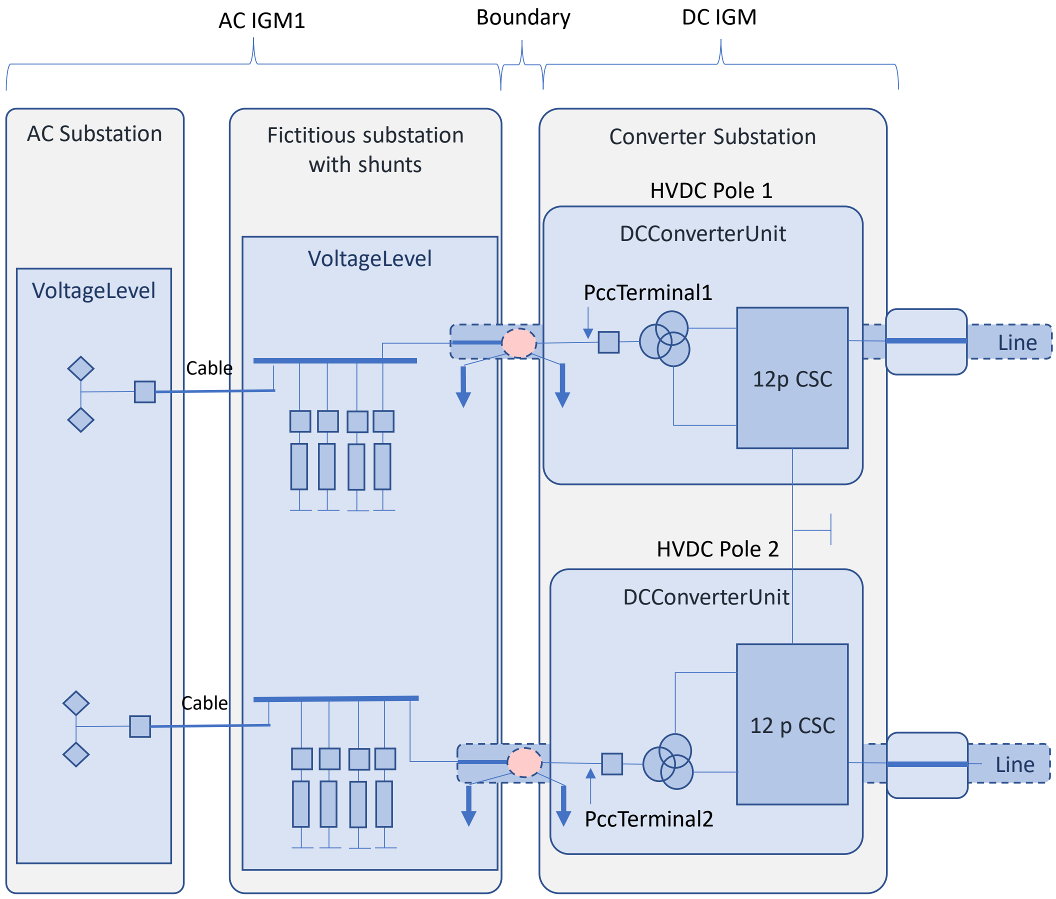


Figure 36 Bipole from example in Figure 35 with boundary between shunts and converter

Figure 36 shows how the two HVDC Poles in each bipole are connected to the fictitious AC Substation with their boundary points between the filters and the converters. The PccTerminal1 and PccTerminal2 shall refer to the cim:Terminal at the boundary side of the cim:Switch. The filters will be at the AC side and connected via the boundary with the converter which enables voltage control using the filters without the DC IGM.

The fictitious substation is needed because the boundary model in IEC TS 61970-600:2017 [1] allow a boundary only within a cim:Line. Note that the fictitious substation needs its own mRID, the mRID from the original substation cannot be reused.

For each pole of a bipole, the boundary contain two cim:Line-s (or HVDC Poles) with a pair of boundary points each.

The case with the boundary between the AC and DC substations is shown in Figure 37.

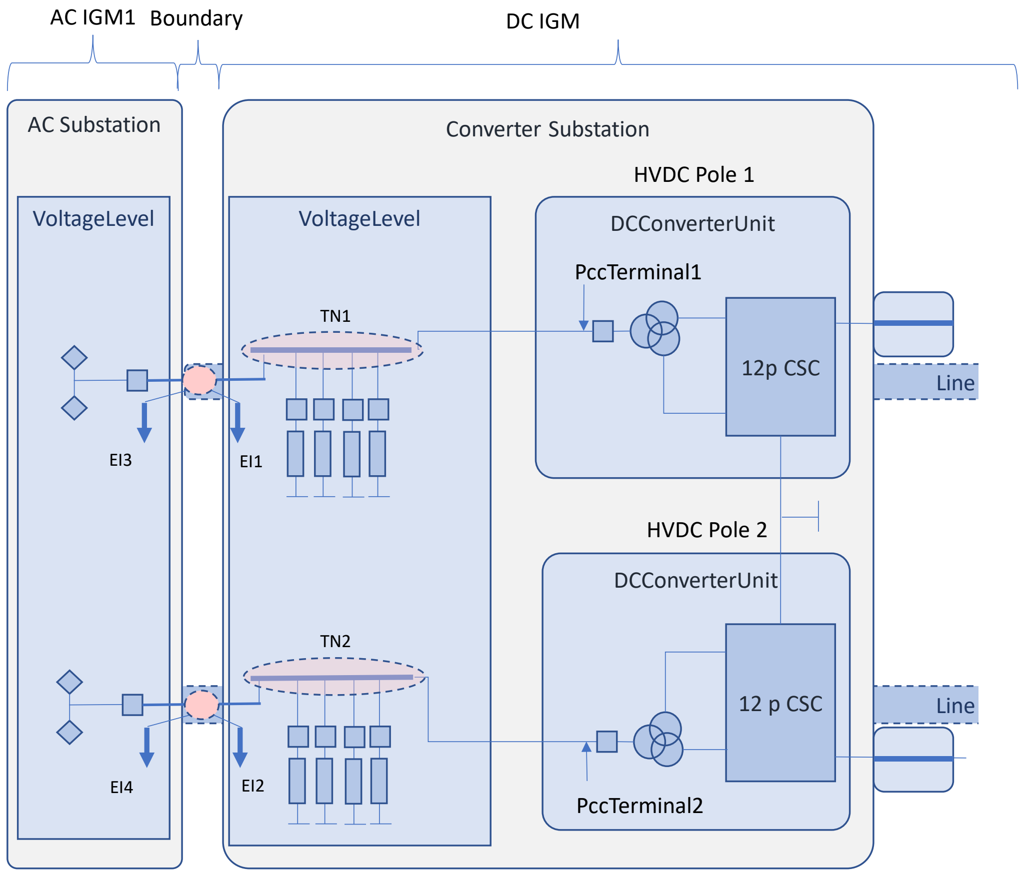


Figure 37 Not allowed HVDC Bipole boundary from example in Figure 35

Figure 37 shows the boundary at the cables between the Converter Substation and the AC Substation which avoids creating the fictious substation in Figure 36. The active power flows in PccTerminal1 and PccTerminal2 are the same as at the boundary points, but an issue with this use cases is that the PccTerminal-s from the CSC (cim:ACDCConverter.PccTerminal) must be associated with the correct boundary cim:EquivalentInjection. In Figure 37 this means linking PccTerminal1 with EI1 and PccTerminal2 with EI2, which needs a topology search starting from the PccTerminal-s, get the TN at the cim:Breaker (TN1 or TN2 in Figure 37), move across the boundary branch to the boundary point and then to the cim:EquivalentInjection (EI1 and EI2 in Figure 37). This topology search is much simpler when boundary is between the VoltageLevel and the DCConverterUnit-s as shown in Figure 36.

Another issue with this boundary configuration the voltage control behaves differently with and without the DC IGM. Without the DC IGM the cim:EquivalentInjection-s in the AC Substation (EI3 and EI4 in Figure 37) will simulate the voltage control behaviour and with the DC IGM the filters are used instead which is more accurate. With the use case shown in Figure 36 voltage control behaves the same with or without the DC IGM as the filter control functionality is the same with or without DC IGM.

The use case in Figure 37 is not allowed due to the above-described issues.

If the two boundary points in Figure 37 are replaced with a single boundary point at points “A” in “Figure 2 Definitions as defined in IEC 60633”in [12], the active power flow in the HVDC Bipole is the sum of the flow in the two individual HVDC Poles which means that the cim:Line represents the HVDC Link rather than each HVDC Pole which is not allowed.

Figure 38 shows Figure 37 where the boundary points has been replaced by a single boundary point like the PCC point "A" in "Figure 2 Definitions as defined in IEC 60633"in.

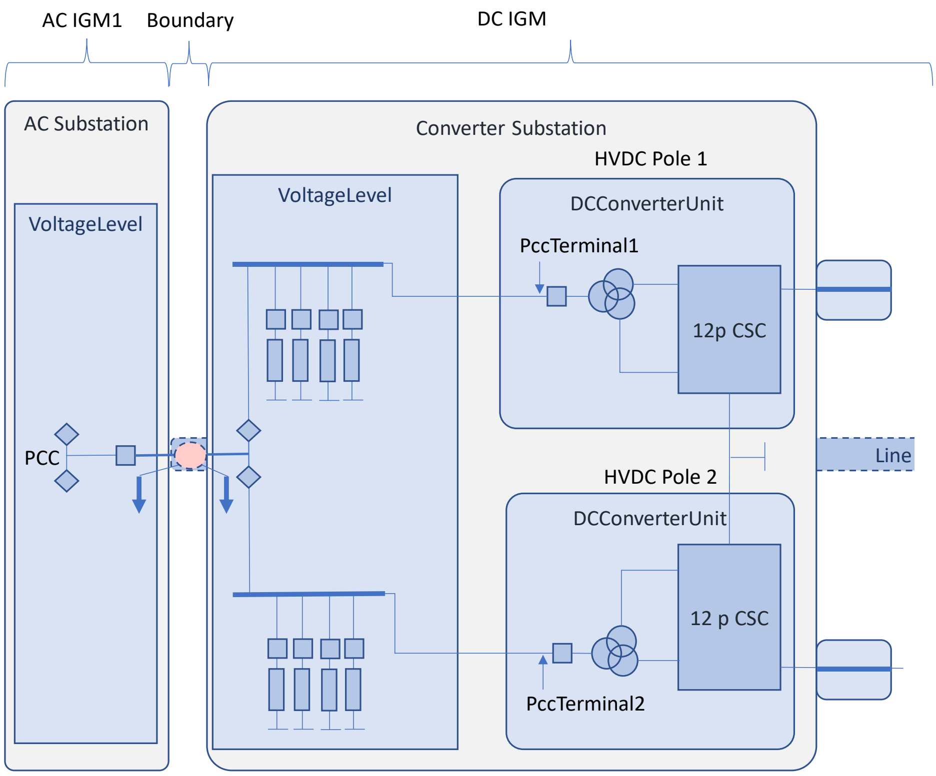


Figure 38 Not allowed HVDC Bipole boundary from example in Figure 35

Having a boundary configuration as in Figure 38 is not allowed as the two HVDC Pole flows at the two PccTerminal-s are not available for assignment of scheduled active power.

12.2.4 Example CsConverter bipole with AC interface

For an internal HVDC Link the active power transfer cannot be related to any specific nodes in the AC boundary without solving power flow. Power flow solve the total exchange between cim:ControlArea-s and an internal HVDC Links will impact at which AC boundary points and tie lines the power is exchanged.

Figure 39 shows the special case where the AC boundary is at two cim:ACLineSegment-s connecting to the AC part of an HVDC Link.

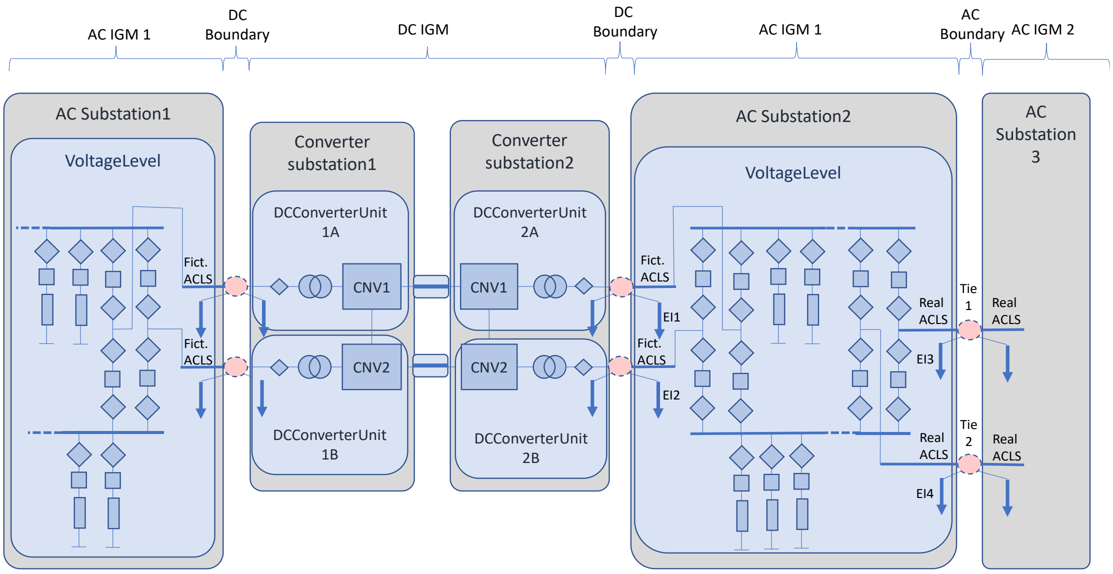


Figure 39 Example bipole with AC boundary at AC Line

Figure 39 shows a detailed DC IGM embedded in an AC IGM 1. The network between AC IGM 1 and AC IGM 2 is two cim:ACLineSegment-s shown to the right in Figure 39. The thick lines labelled “Fict. ACLS” are fictitious cim:ACLineSegment-s and the ones labelled “Real ACLS” are the real cim:ACLineSegment-s. The schedules for the HVDC Poles could be mapped to the AC boundary points Tie1 and Tie2 in Figure 39, but it is not always possible to easily compute the exchange at the tie points Tie1 and Tie2. The solution is to assign the schedule values to the internal HVDC boundary (at the converter substations) possibly by compensation for the losses in the cim:ACLineSegment-s and have the power flow solving the exchange over the AC boundary while keeping the net interchanges between the two cim:ControlArea-s.

13. Voltage source based HVDC interconnection

13.1 VsConverter

13.1.1 VsConverter modelling

This VsConverter modelling use cases are very similar to the diagrams in section 12.2 with the difference that the filters are not needed as the harmonics generation for VsConverter-s are much smaller than for CsConverter-s.

The voltage source converters differ from the current source converters in that both active and reactive power transfer can be controlled independently. The active and reactive power must stay inside a reactive capability curve not to overload the converter. An example reactive capability curve is shown in Figure 40.

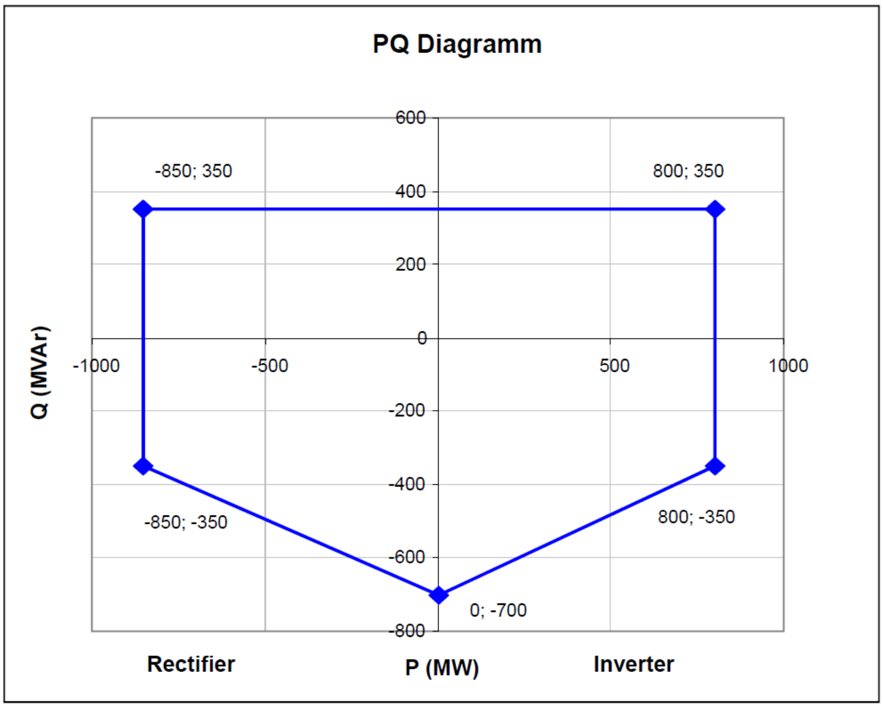


Figure 40 Example reactive capability curve for a VSC

Within the curve, the operation is continuous so no minimum active power limit around zero power is needed as for the CsConverter.

The basic components of a voltage source converter are showed in Figure 41.

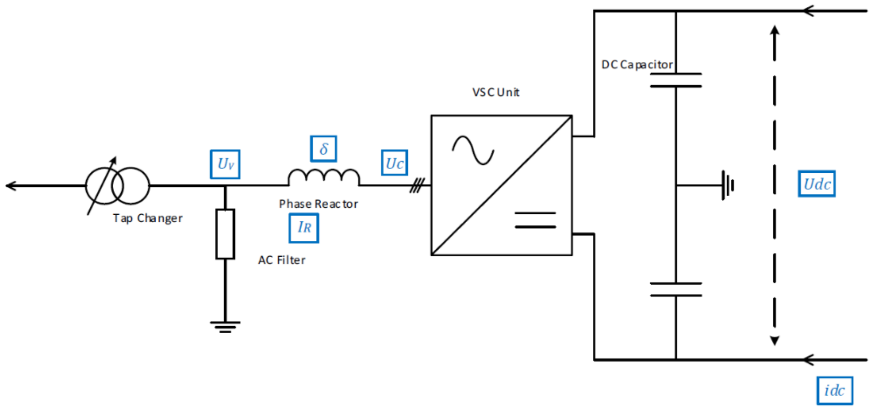


Figure 41 Voltage source converter

Voltage source converters are built with multiple Insulated-Gate Bipolar Transistor (IGBT) that are organized in multiple levels. Each IGBT can be turned off and on which means that they do not depend on the AC voltage for commutation. In modern voltage source converters, the IGBTs are turned on and off at high frequency called pulse width modulation (PWM). PWM together with multiple switching modules (SMs) in series creates an almost harmonics free AC current which result in inexpensive filter solutions.

The active power flow in the converter can be described by the angle between the voltages Uv and Uc while the reactive power flow can be described by the magnitude difference between Uv and Uc, the formulas are:

- $P = Udc*Idc = Uv*Uc*\sin(\delta)/Xc$
- $Q = Uv*(Uv-Uc*\cos(\delta))/Xc$

The variables in the formulas are shown in Figure 41. Additionally, δ is the angle between Uv and Uc. Xc is the Phase reactor reactance, see also IEC 61970-301:2020 for details.

13.1.2 VsConverter control

The PWM pulses are generated according to a hierarchical scheme like the CsConverter. The levels for the VsConverter starting at level 3 in Figure 18 are:

- Converter control
- One side of the converter control the active power with the cim:VsConverter.targetPpcc as input and its own reactive power using cim:VsConverter.targetUpcc for voltage control or cim:VsConverter.targetQpcc for reactive flow control at the PCC.
- The other side control its dc side voltage with the cim:VsConverter.targetUdc and its own reactive power using cim:VsConverter.targetUpcc for voltage control or cim:VsConverter.targetQpcc for reactive flow control at the PCC.
- Switching Module control generates the PWM pulses with inputs from the converter level control. The details for this are out of the scope for this document.

In the same way as for a synchronous machine it can be assumed that that active and reactive power can be controlled independently. As there is no need to consider harmonics nor reactive power compensation similar power flow modelling as for a synchronous machine can be used.

The active power can be managed in several ways:

- Scheduled power where the active power injections are fixed according to a schedule. As the HVDC Link does not participate in load frequency control the link does not participate in keeping the frequency stable.
- Variable impedance where the transferred active power corresponds to the angle difference across the HVDC Link. The HVDC Link exhibits a series impedance and transfer power as a normal cim:ACLineSegment with the difference that the impedance value can be varied. The current CIM does not support this case and it is not in scope of this document but a note to support it in future versions of CIM has been added in Annex B.
- Frequency control in an isolated area connected via an HVDC Link to a main network.

The same equations as showed in Figure 19 apply. The power flow model is the same as in section 11.3. Note that all controls relate to PccTerminal and remote control is not possible.

The reactive power injected by a synchronous machine is a step function where the reactive power injection is a function of the voltage, see Figure 42.

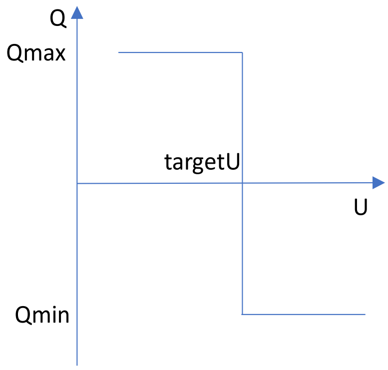


Figure 42 Typical Synchronous Machine Voltage control in power flow

The Qmax and Qmin limits are either from the two fixed limits or from the reactive capability curve. The reactive power injection is solved by the power flow and stays at the vertical line in Figure 42. If a limit is reached the power flow bus is changed to PQ type and the voltage is computed instead. In case multiple machines are controlling the voltage in parallel the reactive net injection is divided on the machine according to some ad hoc method, e.g., by sharing according to the reactive range.

A more accurate model is to describe the response to a voltage change with a droop curve, see Figure 43.

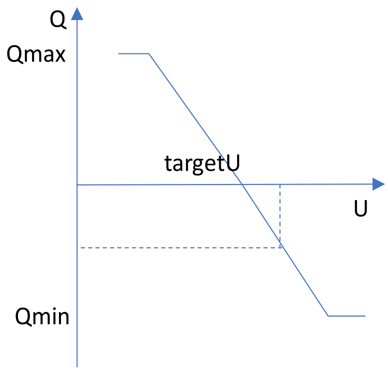


Figure 43 Voltage control droop curve

As the voltage change, see example dashed line in Figure 43, the contributed reactive power will change accordingly. The droop curve describes the real converter response to voltage changes and is typically 2-4 percent.

The attribute VsConverter.qShare describes the sharing between parallel converters and is not a droop coefficient which makes it difficult to combine reactive contributions from other reactive sources, e.g., shunts, synchronous machines and static var compensators (SVC), which has droop control of the voltage.

The different ways to share reactive power supply between to control voltage different equipment need to be discussed in CIM. Best would be if the contribution is described by droop curves.

13.1.3 VSC Modelling Use Case

VSCs does not exist in the many different configurations as SCSs does. Figure 44 shows the single use case.

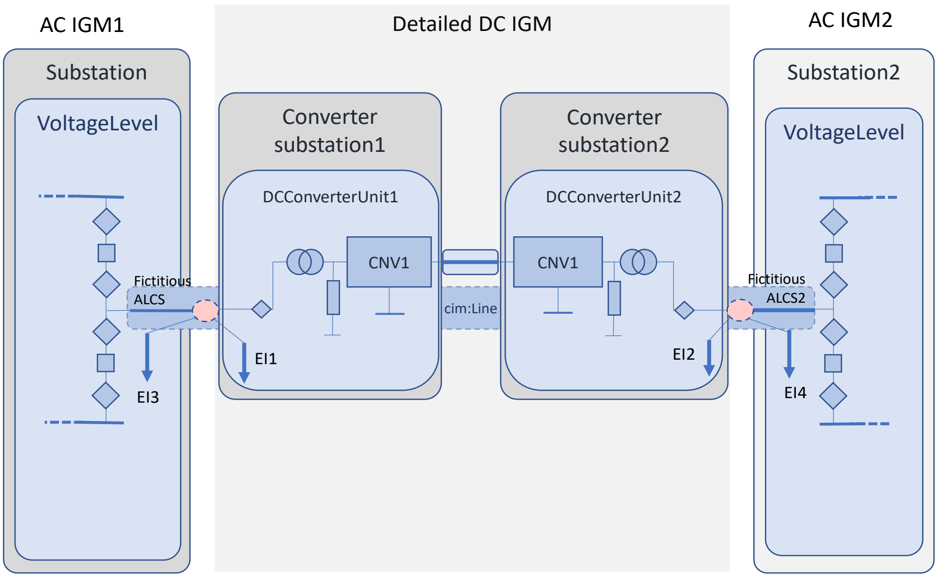


Figure 44 VSC Modelling Use Case

A VSC does not have switchable filters in the AC substation as the VSC provides the reactive power needed to keep the voltage in the AC busbars. The VSC filters are used to remove harmonics which is independent of both active power flow and voltage control. Figure 44 shows the filters located between the converter transformer and the converter (CNV1). It has a single filter, but there may be multiple for different harmonics frequencies, a series filter reactor may also be present.

14. Network data

14.1 UML model

Information modelling in UML can be done in many ways. One way is to be strict on cardinalities which tend to create a more complex UML or use open cardinalities, e.g. [0..*], that allows for a simpler UML. Downside with the latter is that strictness needs to be added later as done with the rules in QoCDC. The complexity avoided with the simplified UML then comes back in the form of way more complex rules at worst described in English text or better described in a formal language as Object Constraint Language (OCL) or SHACL.

The reasons for the many rules needed are the oversimplified UML modelling and the objective to cover multiple business processes with limited number of standards.

For the canonical CIM, IEC 61970-301:2016, the modellers made the choice of a single and deep inheritance hierarchy. For equipment see example in Figure 45.

A deep inheritance structure as in Figure 45 has the benefit of non or only little redundancy, i.e., data is only described once. An example is the cim:Equipment-cim:EquipmentContainer association shown in Figure 46.

The association in Figure 46 is inherited by all subtypes of cim:Equipment (see Figure 45) and cim:EquipmentContainer (cim:Substation, cim:Line, cim:VoltageLevel, etc.). This allows to put any of the cim:Equipment subtypes in any of the cim:EquipmentContainer subtypes where many combinations do not make sense, e.g. cim:SynchronousMachine in cim:Line, cim:ACLineSegment in cim:Substation, etc. There are numerous examples of this in canonical CIM, another is the cim:Terminal-cim:ConductingEquipment association.

Another common issue with the canonical CIM is when combinations of attribute values do not match with the class:

- Some cim:RegulatingControl.mode attribute values do not make sense for some of the subclasses of cim:RegulatingControl, e.g. the activePower control mode is only relevant for phase tap changer transformers.
- For the ENTSO-E extension entsoe:OperationalLimitType.limitType (CGMES v2.4) only a few of the combinations of the limitType values and cim:OperatinalLimit subtypes make sense, e.g. the PATL type is only relevant for branch flows.
- A cim:Switch has two cim:Terminal-s. The attributes cim:Switch.open and cim:ACDCTerminal.connected describe the connectivity status which means there are three ways to interrupt power flow through a switch by using of the open flag or one of the two connected flags.

There are many more examples of this issue.

Yet another issue is when a class is overused to describe unrelated usages, e.g. use of cim:EquivalentInjection (EI) to represent a reduced injection, a boundary injection or an HVDC link. The three cases need to be distinguished from each other and this is done as follows:

- Reduced injection; no specific indication and original use case.
- The flag TN.boundaryPoint[24] where the EI is connected tells the EI represents a boundary injection.
- The text “HVDC” at the TN where the EI is connected tells that the EI represents a HVDC link.

[24] In CGMES v3 this is achieved by the usage of BoundaryPoint class and related attributes. There is no more the need of text “HVDC”, which is CGM BP specific implementation of CGMES v2.4.

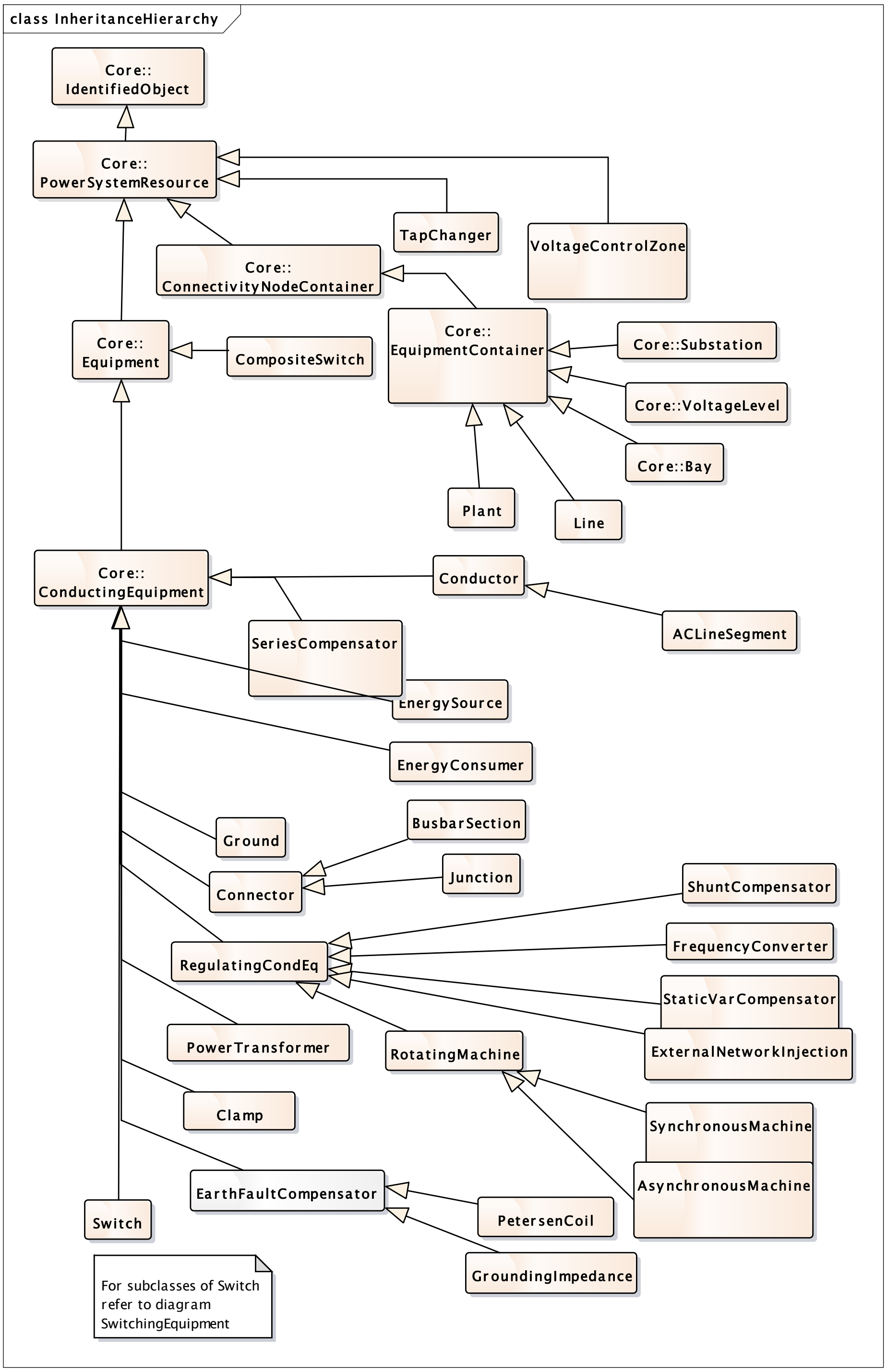


Figure 45 Canonical CIM equipment inheritance hierarchy

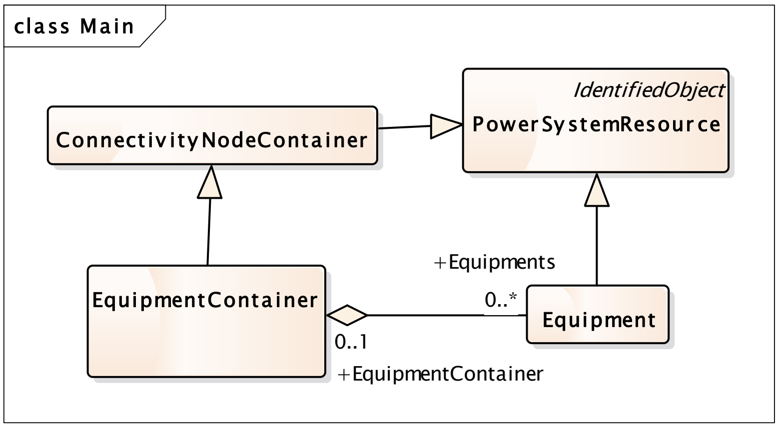


Figure 46 The Equipment-EquipmentContainer association

A better information model would have been to use a dedicated class for each case. When this happens, it is an indication that new and more specific classes are need.

It is possible to create UML models without the above issues but with the consequence of more complex UML models and potentially breaking changes.

A way to restrict a too open UML model is to constraint the modelling within the profiles and use rules described in the Object Constraint Language (OCL) that works together with the UML information model. This increases the complexity of the information model and if CIM was to be refactored in the future the trade-off between a more restrictive class model in UML or use of OCL rules could be investigated.

The least intrusive way to restrict the current CIM information model is to use OCL rules, which is extensively used CGMES v2.4. The restrictions are described in the QoCDC. SHACL (W3C Shape constraint language) is another way of defining constrains which was chosen for CGMES v3 profiles.

14.2 Rules

Rules that describe the quality of network data can be divided in groups describing increasingly complex relations in data:

A. Most basic are schema rules defined by the profiles derived from canonical CIM UML. The profiles are formally expressed in an XML format described in IEC 61970-501:2006.

B. Restrictions of values that cannot be described in UML, e.g., relations as x<y and string lengths.

C. Additional restrictions on too open role cardinalities, e.g. switches shall have exactly two cim:Terminal-s.

D. Additional restrictions on combinations of data where role references are followed to collect and cross check data from different classes. Several of these restrictions are defined in IEC TS 61970-600-1/2:2017, but many new restrictions have been added based on experiences from interoperability tests.

IEC 61970-501:2006 is XML format based on the RDFS specification:

- www.w3.org/TR/1999/PR-rdf-schema-19990303

The specification is outdated and since 1999 both the OWL specification and the RDFS 1.1 specification from 2014 has been created. The custom IEC 61970-501:2006 extensions are now covered by the latest OWL and RDFS specifications and IEC 61970-501:2006 needs to be revised.

Validation according to QoCDC is done in the two steps "CIMXML file validation" and "Model validation" shown in Figure 3.

"CIMXML file validation" is done within the scope of the CIMXML file and includes:

- Level 2 profile schema validation according to group A above. This means checking that class, attribute and role names in XML elements match the profile schema and that cardinalities are respected.
- Level 3 additional validation according to groups B, C and D. Groups C and D use local associations within a CIMXML file.

"Model validation" is done for an assembled model and includes level 5 and up in Figure 3. The rules have a scope according to groups C and D above. Groups C and D use data not possible to check within a single CIMXML document.

14.3 Containment

The physical equipment in a power network is organised in a structure starting with geographical regions having substations having bus bar systems having equipment and so on. IEC TS 61970-600-1/2:2017 enforces a containment structure suiting transmission network. The reasons for IEC TS 61970-600-1/2:2017 doing this are:

- It keeps fidelity with how transmission networks are built.
- It enables recognition of objects across different types of models. In a bus-branch model that do not include substations, the bus names may imply the substation, which makes mapping between simplified and detailed models difficult.
- Tools commonly rely on the containment structure for model navigation.

The substation is an important concept that describe equipment located in fenced area of limited size. Substations are electrically connected with other substations by transmission lines.

The bus bar systems within a substation is called cim:VoltageLevel and include the bus bars (cim:BusbarSection in CIM) and equipment.

In a real substation all equipment is included in bays but in CIM only switches are in a cim:Bay.

Some misuses of substation containment are:

- A single cim:Substation for the whole network.
- One cim:Substation per busbar system which means that every cim:Substation include exactly one cim:VoltageLevel despite transformers in the cim:Substation resulting transformers spanning multiple substations.

CGMES v2.4 has gaps in specifying containment rules. CGMES v3 is the first standard that precises the requirements for each equipment.

14.4 Disconnecting switches

Switches can be disconnected with the following three attributes in series:

- The cim:Switch.open flag
- Either or both cim:ACDCTerminal.connected flags

This allows for variation, as shown in Figure 47, that complicates solutions.

1. Closed path
2. Open path Switch open and ACDCTerminal connected
3. Open path Switch open
4. Open path ACDCTerminal connected

- Options for less variations on Switches

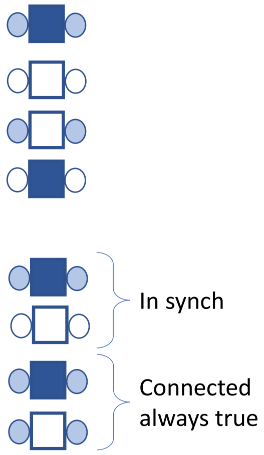


Figure 47 Combination of cim:Switch.open and ACDCTerminal.connected flags

Hence the cim:ACDCTerminal.connected flag for cim:Switch-es shall always be true. This avoid caring about these flags for cim:Switch and its subclasses. Level 5 rule SwitchOpenVsConnected also checks this.

14.5 Node-breaker vs. bus-branch modelling

There are different styles of modelling of a power system network in terms of connectivity and switching equipment. The choice of modelling style is driven by the requirements of the business processes that utilise the models. A node-breaker modelling style normally includes enough switching equipment in order to perform substation reconfiguration and studies that require operations of the switching equipment. A bus branch modelling style represents a simplified view of the topology, normally a result of a topology processing in which process non retained switching equipment are logically eliminated to form topological nodes that connect zero impedance equipment. Models that can be classified as node breaker models can have different level of detail. For instance, a very detail node breaker model can include disconnectors and other detail representations necessary for SCADA/EMS type of modelling, but at the same time a node breaker model could also be a model that includes breakers, but not disconnectors and other details. All depends on the detail needed for the studies. Data exchange standards are only allowing the exchange of models without dictating the way of modelling[25].

Bus-branch models are simpler than node-breaker models which is beneficial in planning scenarios while node-breaker models are used in real time systems (SCADA/EMS) where the power flow input and result is mapped to real equipment. Once a detailed node-breaker model has been created there is no reason to have a bus-branch model maintained in parallel with the node-breaker model. This result in extra work keeping the duplicate models coordinated. Better is to derive the bus-branch model from an already existing node-breaker model, also called topology processing. In any case power flow calculation is normally computed on that state of the grid after a topology processing.

A power flow performs the calculation on network with branch impedances and injections using

[25] For example, it should not be understood that CGMES v3 requires node breaker model exchange, which is not true. CIM supports both bus-branch and node-breaker modelling but CGMES v2.4 lacks detail on how to do it which leads to several different interpretation ways. This is clarified in CGMES v3.

Ohm's and Kirchhoff's laws. The branches and injections are connected at "fictive power flow busses", hence the term "bus branch model". In CIM the "fictive power flow busses" are represented by cim:TopologicalNode-s (TN).

Closed switches represent a zero impedance, which a power flow calculation does not handle easily. There are two approaches:

1. Represent closed switches with an impedance small enough not to impact the solution but big enough to enable power flow convergence. This has consequences:
   - May result in numerical instability when solving power flow.
   - Result in large matrices which degraded performance and increased need for memory space.
2. Remove all closed switches and merge the switch connection points called topology processing. This has consequences as well:
   - Topology processing is needed.
   - Mapping issues between the node breaker and bus branch models, e.g., transferring the power flow solution back to the objects replaced in topology processing.

Node-breaker modelling with CIM is supported by the class cim:ConnectivityNode (CN). To summarise CNs and TNs according to approach 2 above:

- CNs describe the as built network with or without switches.
- TNs describe the fictive power flow busses and are computed by topology processing when processing the switches.

In CGMES v3 all models are built using cim:ConnectivityNode-s, irrelevant of the chosen modelling style, node breaker or bus branch.

Figure 48 shows what an architecture supporting topology processing.

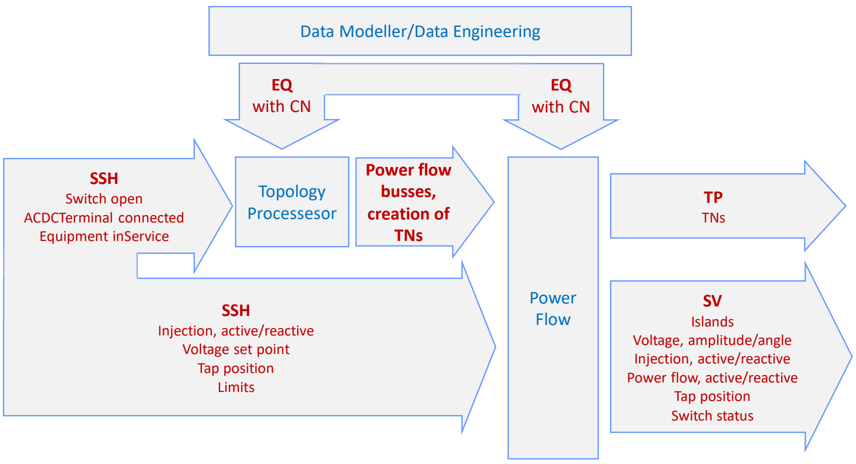


Figure 48 Architecture with topology processing[26]

The as built CNs come from a Data Modeller or Data Engineering tool where they are maintained. The CNs and all equipment connected to them are fed into the Topology Processor that creates the TNs, hence the TNs are a result.

[26] Note Equipment inService is attribute present in CGMES v3.

Figure 49 shows the bus-branch model example, mainly used for the planning models. Simplifications can occur and if switches are to be modelled, those would have to be retained.

Figure 50 provides one option of the switching status of the similar grid represented in Figure 49, but more detailed, similar to SCADA and EMS systems representation. It is presumed that the switches are contained in cim:Bay and not retained. The same grid is represented in Figure 51, with the indicated breaker opened, resulting in two cim:TopologycalNode-s created as results of the topological processing (14.6). In these two figures, it is clearly visible why TP CIMXML file is to be considered as output in case of switching status changes.

The changes of the switching status is not foreseen as part of current CGM creation process where TP CIMXML files are necessary inputs.

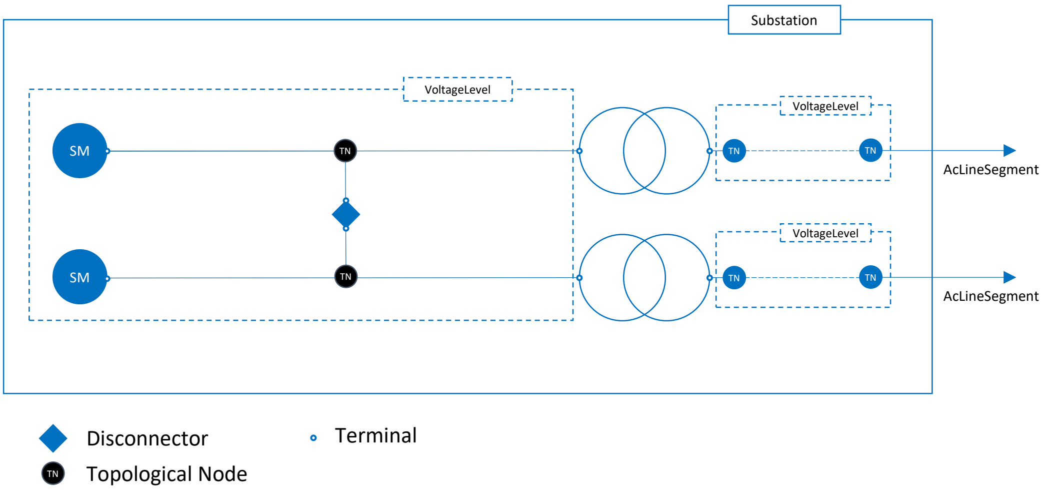


Figure 49 Bus-branch model example[27]

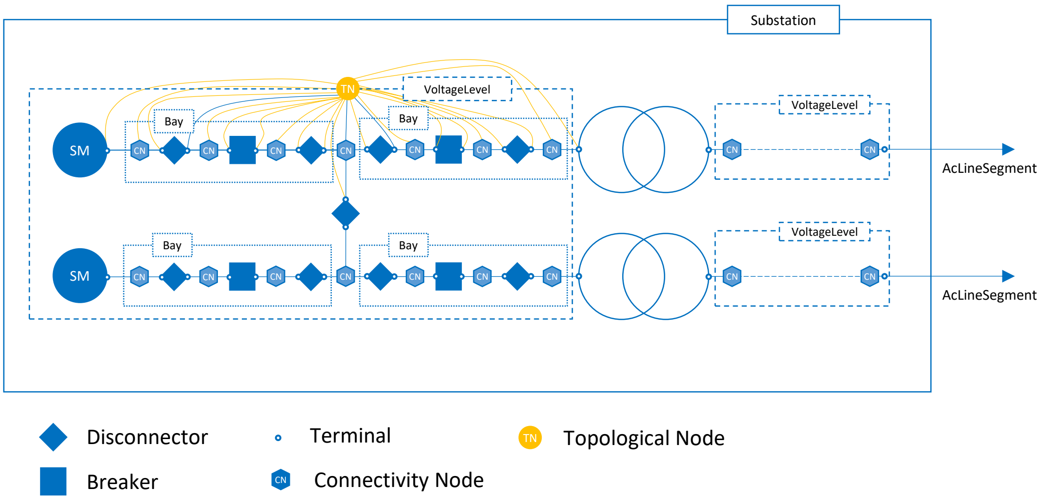


Figure 50 Node-breaker model example with topological processing option 1[27]

27 CGMES 2.4

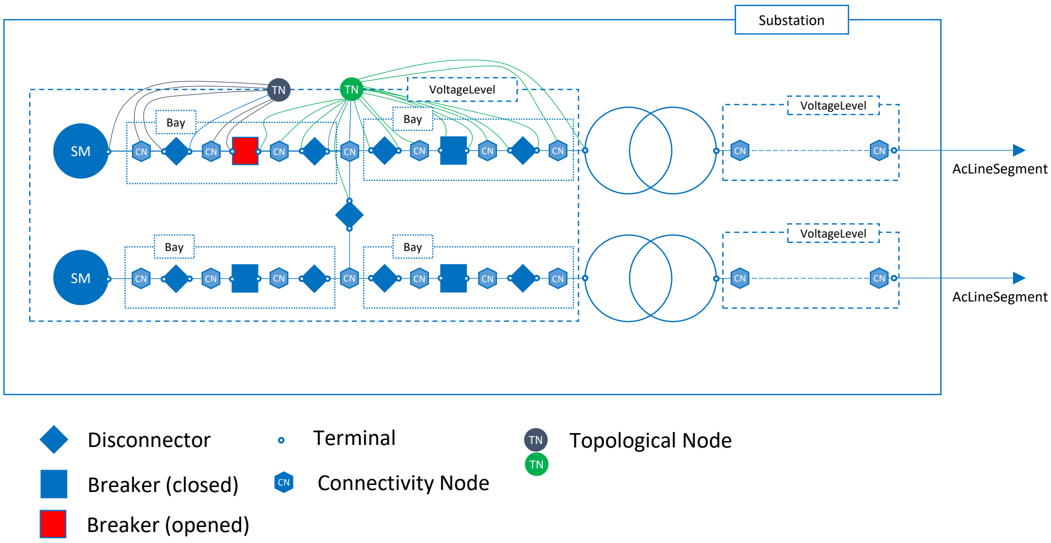


Figure 51 Node-breaker model example with topological processing option 2[27]

Figure 52 shows the TNs for an open-ended branch in case where no topology processing is made. The TNs in the as built model are not updated and no TN to describe the left open end is available, hence the voltage at the open end cannot be reported.

When topology processing is computed for the TNs in case of an open-ended branch, new TN is created and the voltage can be calculated and reported.

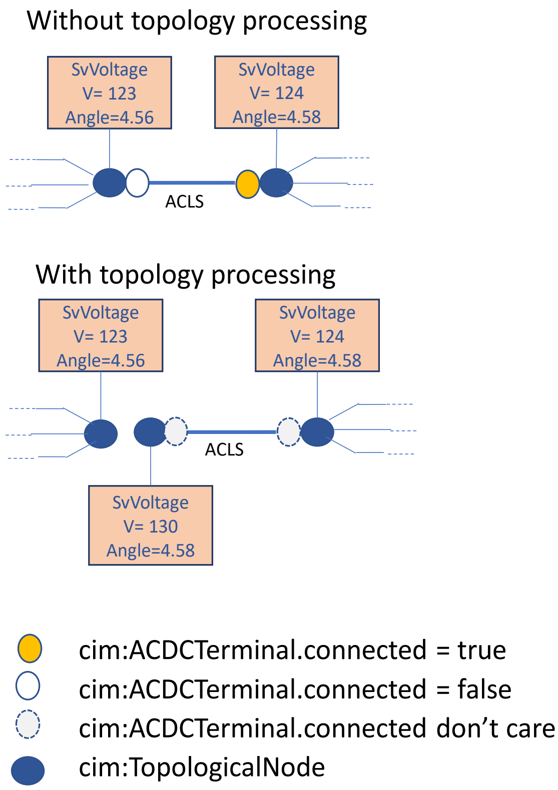


Figure 52 Open ended branch in bus-branch model

A common solution to this in bus-branch tools is not to allow open ended branches.

A solution that avoids the issues is to use CNs for the as built model, which means that the Data

Modeller or Data Engineering tool is using CNs as in Figure 48. TNs are not used in the as built model but are created by topology processing. This has many benefits[28]:

- A model that starts as a bus-branch without switches can be gradually refined by adding switch details. There are already several examples of IGMs where bus-branch and node-breaker styles are mixed in the same model.
- Network extensions are initially created as bus-branch models for study purposes and once the equipment is designed and built the original bus-branch model is extended with the detailed as built design.
- The issue with open ended branches disappears as the needed dead end TNs are created by topology processing.
- The boundary can be simplified to only contain CNs. TNs and the CIMXML TP boundary file are no longer needed, which simplifies the assembly process.

14.6 Topology processing

The purpose of the Topology Processing function shown in Figure 48 is to create the cim:TopologicalNode-s (TN) from the cim:ConnectivityNode-s (CN) connected by closed (cim:Switch.open=false) and not retained (cim:Switch.retained=false) switches. The topology processing can also eliminate other zero impedance branches depending on zero impedance threshold and capabilities of power analysis applications.

Switches that are retained (cim:Switch.retained=true) are treated as branches and are kept, which means that their two ends (cim:Teminal-s) shall always be connected to two different TNs. If this is not the case after topology processing, there may be another path with closed and non-retained switches between the two TNs. This is a modelling error and the IGM needs to be corrected.

For CGMs, TNs are used as input as shown in Figure 7. This means that the TNs shall be used as is and no topology processing be made. A merging tool may still do topology processing for NB IGMs included in the CGM to check that the provided TNs are correct. Despite any errors found the provided TNs shall still be used in the power flow calculation.

Creating TNs from CNs and closed switches is straight forward and can be summarized by the following graph search process. Note that this is just an example implementation. There could be many other ways:

1. Select an arbitrary CN and create a TN for the selected CN.
   a) Stop when all CNs have been visited.
2. For the selected CN
   a) Collect all neighbouring CNs connected via closed switches or other zero impedance elements and add to CNs to be processed. Link all switches connected to the CN also to the TN (create reference cim:Terminal.TopologicalNode, see also section 14.8).
   b) Collect all branches and injections and link them to the TN (create references cim:Terminal.TopologicalNode).
3. Abandon the selected CN and select a new CN from the set of CNs to be processed.
   a) If a CN was found continue at 2

[28] These are the directions that were integrated in CGMES v3.

b) If no more CNs in the set to process continue at 1.

This algorithm creates TNs for all CNs that are connected via closed switches and each TN will have injecting equipment and branches connecting with other TNs. Not all IGMs create TNs like this, there are IGMs with the following deviations:

- Shunts with open switches that are still connected to an energized TN but with the cim:ShuntCompensator.sections=0 and/or cim:ACDCTerminal.connected=false. See section 14.17 for a discussion of this.
- Not energized TNs with a seemingly ad hoc collection of equipment. If such TNs are kept not energized they will not disturb the power flow solution but if energized they may disturb the power flow solution.
- TNs with erroneously connected equipment and branches, in this case the power flow solution is impacted.

14.7 TopologicalIsland

A cim:TopologicalIsland consists of cim:TopologicalNode-s (TN) that are connected by branches with non-zero impedance. A power flow solves each cim:TopologicalIsland individually. In CGMES v3 an important clarification was made that topological islands contain only energised nodes and solution is only exported for energised nodes while in CGMES v2.4 solution is also reported for deenergised cim:TopologicalNode-s.

cim:TopologicalIsland-s group synchronously connected TNs that can have power flow solution. Hence the islands are an important tool to analyse and compare power flow results with big differences. The following checks when comparing can then be made:

- Islands are the same with same TNs
- Convergence statuses are the same for the islands, i.e., power flow was run for all islands and whether it converged or not.
- Synchronous areas in a CGMs are reported as separate cim:TopologicalIsland-s simplifying inspection of the synchronous areas.

TNs in the same cim:TopologicalIsland shall be electrically connected. Hence all TNs in an island have the same electrical status. The statuses are:

- Energized – the power flow solved for the island and non-zero injections present.
- Deenergized – the power flow solved for the island and all injections are zero.
- Diverged – the power flow did not solve the island.

QoCDC has introduced an option to provide the status of the islands, which is a voluntarily modification of CGMES v2.4 (not to interfere with conformity assessment) where the cim:IdentifiedObject.description text of a cim:TopologicalIsland may exist and contain one of the texts:

- "Converged" for a converged solution.
- "Diverged" for a diverged solution.
- No other texts are allowed, if cim:IdentifiedObject.description is introduced for cim:TopologicalIsland.

The voltage and angle for TNs are set as follows:

- For an energized island the voltage and angle are non-zero except for the angle reference node where the angle is zero.
- For a deenergized or diverged island all voltages and angles are zero. Information about divergence is given by the power flow convergence report.

In CGMES v3 this is not required as solution is exported for energised TNs only, which makes the reporting of the solution result clearer and stimulates the improvement of model quality.

In diverged islands the computed injections and power flows in cim:SvPowerFlow shall be zero. This information does not enable unique interpretation, as zero could also mean that the node is deenergized. The rules in QoCDC that check the resulting power flow in SV with the input conditions in SSH will report errors or warnings due to this. To properly handle diverged islands, rules that check the resulting power flow require special logic to only check energized islands where cim:SvVoltage-s have nonzero voltage.

Small (typically too small to create a meaningful solution, see also rule SmallTopologicalIsland in QoCDC) and deenergized cim:TopologicalIsland-s is typically the result of topology processing where a few connected CNs are isolated and with zero injected power, e.g.

- Disconnected busbar section
- Open switches connected to a common CN
- Injections not delivering any power.

Such cim:TopologicalIsland-s shall not be exported as they do not add any value and clutter a solution.

14.8 Terminal to TopologicalNode reference

The reference cim:Terminal.TopologicalNode has cardinality 1 (required) in the TP profile but wording in IEC TS 61970-600-1:2017 section E.17 allow for exclusion of cim:Terminal.TopologicalNode from the CIMXML TP file when switch details are reduced away.

This has the consequences that:

- The voltage and angle on each side of a cim:Switch cannot be reported as cim:Terminal-s are missing cim:Terminal.TopologicalNode.
- If the cim:Terminal at a cim:Switch is controlled by a cim:RegulatingControl or cim:TapChangerControl, see section 14.10, the reference to the controlled TN is lost and control cannot be performed.

Hence all cim:Terminal-s shall have cim:Terminal.TopologicalNode according to the cardinality.

14.9 Switch retained

The cim:Switch.retained flag tells a power flow calculation to compute the power flow through a closed cim:Switch. This may be implemented by keeping the cim:Switch as a low impedance branch in the bus-branch model as discussed in section 14.5 approach 1.

The purposes of having retained cim:Switch-es are:

- Computing the power flow through a closed cim:Switch, this is useful both in node-breaker and bus-branch models.
- Allowing bus splits in a bus-branch model without having to edit the connectivity. It is common to make bus couplers retained for this reason.

14.10 Control configuration

The CIM allows modelling control in several ways. This section discusses the options and their consequences. As basis for the discussion the diagram in Figure 53 is used.

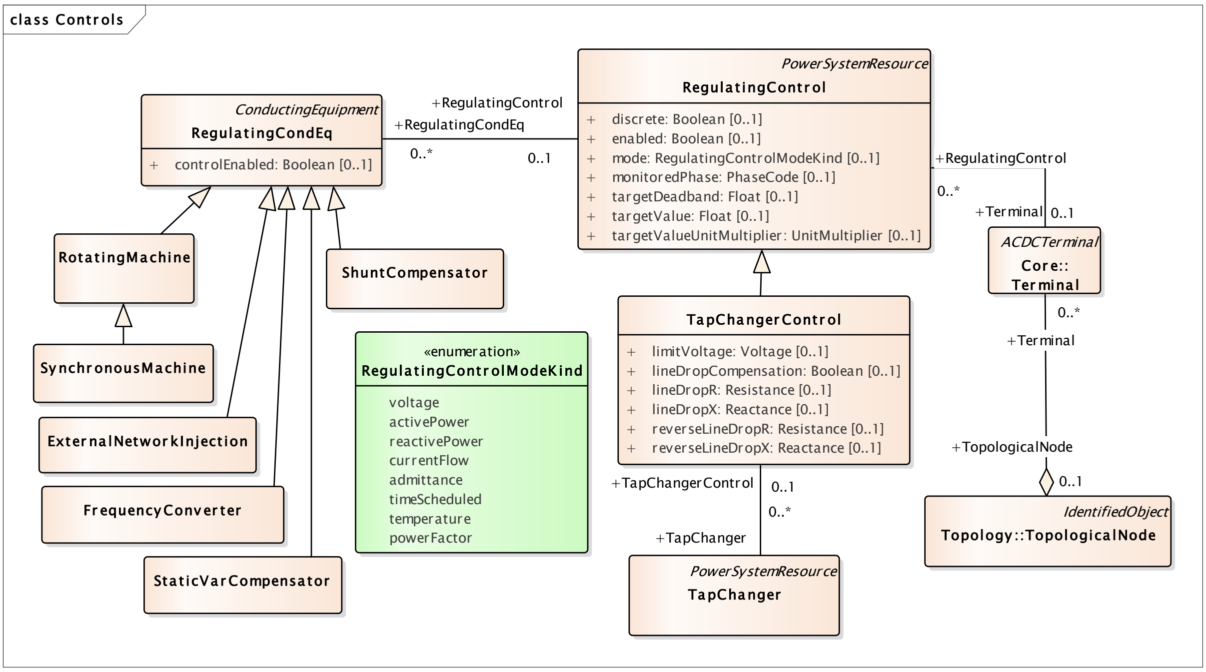


Figure 53 CIM for control

Figure 53 convey the following information:

- Controlling equipment is linked to a cim:RegulatingControl. The controlling equipment could be a subtype of
- cim:RequlatingCondEq
- cim:TapChanger
- A cim:RegulatingControl or cim:TapChangerControl may have many controlling equipment's.
- The quantity that cim:RegulatingControl controls is located at a cim:Terminal.
- A cim:Terminal may have many cim:RegulatingControl-s or cim:TapChangerControl-s.
- A cim:Terminal is linked to a cim:TopologicalNode.
- A cim:TopologicalNode is where a power flow calculation control the quantity.
- A cim:TopologicalNode may have many cim:Terminal-s.

This gives several ways to instantiate the classes in Figure 53 as shown in Figure 54.

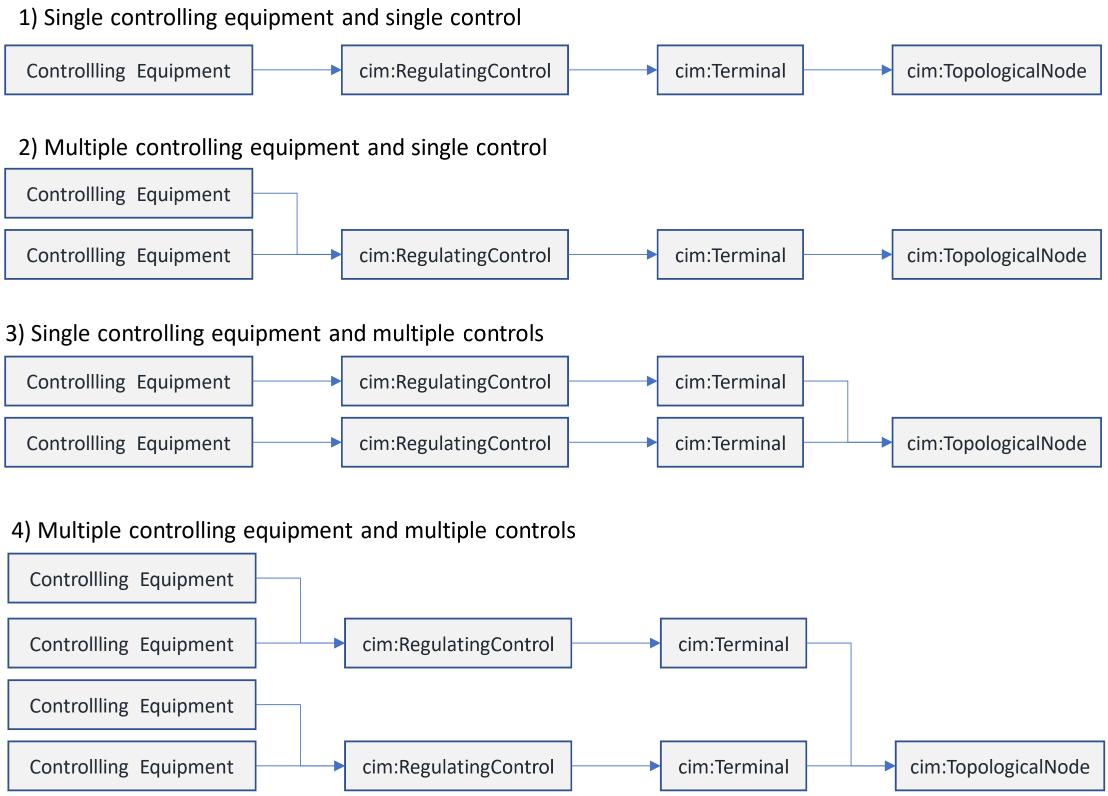


Figure 54 Control configuration cases

Cases 1 and 2 in Figure 54 are simple and without issues related to the control (cim:RegulatingControl or cim:TapChangerControl).

Cases 3 and 4 may have conflicts between cim:RegulatingControl.targetValue and cim:RegulatingControl.targetDeadBand between the different controls. The cim:RegulatingControl.targetValue-s should all be the same but the cim:RegulatingControl.targetDeadBand-s may differ depending on the controlling equipment, e.g. a tap changer may have a small dead band while a shunt may have a large.

In cases where multiple controlling equipment control the same TN the conclusions are:

- Use a single control to avoid target value conflicts.
- Use multiple controls only when different dead bands are needed.

In a node breaker model, it is possible to change the TN by switching. In a real substation, breaker and bays may allow for extensive reconfiguration of TNs, see Figure 55.

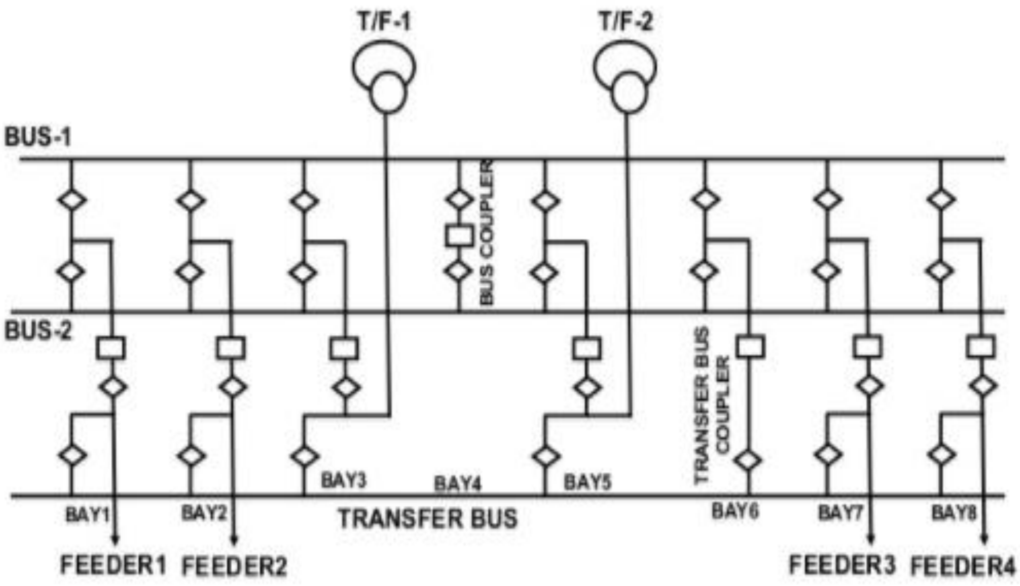


Figure 55 Example node breaker substation

The substation in Figure 55 has two main bus bars BUS-1 and BUS-2 and one transfer bus. The two machines T/F-1 and T/F-2 may be on different or the same TN depending on the switches. The control for machines T/F-1 and T/F-2 may be according to case 2) or case 3) in Figure 54. For the controlled cim:Terminal-s this results in the following options:

1. With a single control (case 2) the controlled cim:Terminal could be at:
   a) one of the machines
   b) a switch
   c) one of the bus bars
2. With two controls (case 3) the controlled cim:Terminal could be at:
   a) one of the machines
   b) each of the machines
   c) a switch
   d) any two switches
   e) one of the bus bars
   f) any of two bus bars

With all options except 2b it is easy to lose the control by switching. In option 2b the control follows each machine to the TN where the machine is connected but if both machines are connected to the same TN the target values may instead conflict.

In a real substation it is common that the controlled point is located where the measurements are, e.g., at a breaker or bus bar. As concluded above this does not fit well with the need to make power flow calculations work with CIM data. Hence the CIM information model for control is insufficient and needs revision[29].

[29] ENTSO-E Network Code EquipmentReliability profile introduces an enhanced model for the controls.

If the controlled cim:Terminal belong to a cim:Switch and a topology processor do not include cim:Terminal.TopologicalNode in the CIMXML TP file this is another reason for loss of control capability, refer to discussion in section 14.5.

14.11 Equivalents

14.11.1 EquivalentInjection

The class cim:EquivalentInjection has three different usages:

3. Represent boundary flows between IGMs.
4. Equivalent representation of HVDC flows.
5. Reduced network parts in a model.

Case 1 is distinguished by the cim:EquivalentInjection-s being connected to a boundary TN or CN.

Case 2 is distinguished by the cim:EquivalentInjection(s) being connected to a boundary TN or CN with the text “HVDC” in the beginning of the TN or CN cim:IdentifiedObject.description attribute (CGMES v2.4).

Case 3 distinguished by the cim:EquivalentInjection-s not meeting case 1 or case 2.

Case 1 and 2 require an assembly between EQ and EQBD CIMXML files to be determined.

14.11.2 EquivalentBranch

Cim:EquivalentBranch-es may include transformers, hence they may span between different base voltages. But cim:EquivalentBranch-es do not have the attribute phaseAngleClock so phase angle displacement cannot be described. Hence cim:EquivalentBranch-es cannot be used to describe transformers with non-zero cim:PowerTransformerEnd.phaseAngleClock. In this case a cim:PowerTransformer must be used.

14.12 LoadResponseCharacteristic

Merging agents shall ignore cim:LoadResponseCharacteristic instances with exponential dependency on voltage (cim:LoadResponseCharacteristic.exponentModel = true). The load given by cim:EnergyConsumer.p and cim:EnergyConsumer.q shall be used as is without using the equations for voltage dependency.

TSOs may use instances of cim:LoadResponseCharacteristic with exponential dependency on voltage. If used the load values (cim:EnergyConsumer.p and cim:EnergyConsumer.q) shall be specified at nominal voltage. If the power flow solution ends at another voltage than nominal the load will deviate from the nominal and the resulting load is given by cim:SvPowerFlow p and q.

14.13 Line taps and T-points

A transformer at a transmission line is sometimes modelled as an injection at the line, a “tap”. High voltage transmission lines typically do not have taps, but lower voltage distribution feeders have.

Network models used in processes described in this document do not include low voltage feeders with taps. If a transmission line has a tap, switching equipment as well as a transformer is normally present, hence the tap shall be described being within a cim:Substation and not in a cim:Line.

A cim:Line may have a T-point with an additional cim:ACLineSegment branches off from the line.

A T-point in a cim:Line has three cim:ACLineSegment-s connected to a CN/TN. More than one T-point may exist in a cim:Line.

14.14 Voltage levels and boundary points

CGMM (Common Grid Model Methodology) defines the level of detail that is required. However, TSOs may have a need to model lover voltage levels, e.g., 110 kV if this is considering important for the representation of their grid. It is not uncommon that there are interconnections between the TSOs of these lower voltage levels. Not coordinating level of modelling between neighbouring TSOs would result to unpaired boundary points which can lead to different treatment of these interconnections in the process where IGMs are processed. Therefore, the following is recommended:

- TSOs should agree bilaterally on the level of detail of lower voltage levels around their borders and ensure that there are no unpaired boundary points, i.e., each boundary point is connected/referenced from the two TSOs.
- As part of the operational process TSOs should agree on the status of all interconnections so that this is considered in the preparation of their IGMs. TSOs should ensure that when their IGMs are merged with neighbouring TSOs the elements connected to the boundary points have the same status, e.g., lines are either in operation or not. This is important for the CGM building process and further usage of the CGM in business processes. Not following this will result to switching off of interconnections which would have impact in the quality of CGMs.

14.15 Production in distribution networks

Production may be embedded in distribution networks, e.g., in case of renewable production. The distribution network typically connects to the transmission network at a transformer. The flow through the transformer will then have both a load and production component. If the flow is modelled as a load, e.g. a cim:ConformLoad, the expected load variation curve during a day will be distorted by the production component. To remedy this the load and production shall be modelled separately, i.e.

- The load shall be modelled by a cim:ConformLoad (housing) and/or cim:NonConformLoad (industrial) depending of the behaviour.
- The production shall be modelled by an aggregate cim:SyncronousMachine or cim:EquivalentInjection. Both have voltage control capability that may be utilized if the production has reactive resources.

14.16 StaticVarCompensator (SVC)

14.16.1 Overview

Reactive power output of a cim:StaticVarCompensator (SVC) is limited by the capacitive and inductive ratings representing the maximum and minimum susceptance values derived from reactive power output of capacitor and reactor banks. In normal operations these limits are not often reached.

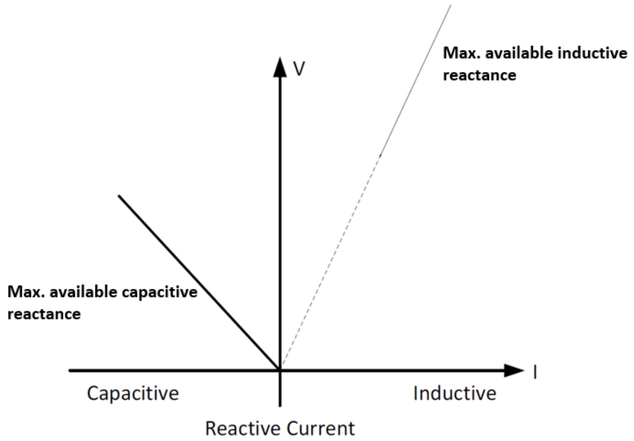


Figure 56 Capability curve for a SVC

The min/max reactive power of an SVC determined by:

$$Q_{min/max} = -\frac{V \times V}{rating}$$

Where:

- rating is the capacitiveRating or inductiveRating
- V = local voltage at the SVC. Even when in remote regulation, the local voltage shall be considered to retrieve the minimum or maximum local reactive output.
- Minus sign in equation according to:
- IEC 61970-600-2:2017 The value of the inductiveRating is negative, the value of the capacitiveRating is positive.
- IEC 61970-301:2016 positive current indicates an inductive current as load sign convention is used.

14.16.2 Implementing Control

IEC 61970-301:2016 and IEC TS 61970-600-2:2017 do not specify if the local SVC control attributes shall be used or the cim:RegulatingControl attributes. As the cim:RegulatingControl describes the controlled point in the network (a cim:Terminal), cim:RegulatingControl shall be used and not the SVC local attributes:

- cim:StaticVarCompensator.sVCControlMode
- cim:StaticVarCompensator.voltageSetPoint

This is clarified in CGMES v3 and these attributes are deprecated not to duplicate information.

cim:StaticVarCompensator.q may be used as a reactive starting point in power flow. It shall not be used as targetvalue for a reactive regulation.

cim:RegulatingControl.enabled defines whether the regulation is enabled. When the attribute is false, it means the regulation is off and the reactive output of the SVC shall be zero Mvar.

An SVC may operate in fixed Mvar output mode or in voltage control mode. This is defined by the RegulatingControl.mode which for an SVC could be voltage or reactivePower.

14.16.3 Voltage Control

When the cim:StaticVarCompensator.slope is zero, the SVC will inject or absorb reactive power to reach the voltage target as long as capacitiveRating or inductiveRating limits are not reached.

When the cim:StaticVarCompensator.slope is positive, the reactive output of the SVC is defined by:

$$Q = \frac{V_{bus} - V_{ref}}{slope}$$

Where:

- cim:StaticVarCompensator.slope is positive based on the load sign convention.
- Vbus is the voltage at the controlled point determined by cim:RegulatingControl.Terminal which may be local or remote.
- Vref is the target value given by cim:RegulatingControl.targetValue.

14.16.4 Reactive power control

According to IEC 61970-301:2016 an SVC in reactive power control keeps the susceptance constant. This is not correct and in reality, the reactive power flow at controlled point is kept constant by varying the susceptance so the SVC absorb or inject reactive power to reach the reactive target value at the controlled point.

The reactive power control could apply both to a local or to a remote-controlled point. In case of remote-controlled point, load-flow tools should assess the direction to change reactive power flow on the SVC.

14.17 Shunt compensators

Shunt compensators are often used in power flow to control voltage. It is also common they are used together with equipment with continuous control capability as synchronous machines and static var compensators with the purpose to keep continuous resources in the middle of their control range. A way to solve this in a power flow is to let the shunts control the reactive power flow from the continuous resource so the flow is close to zero. This can be done with the configuration shown in Figure 57.

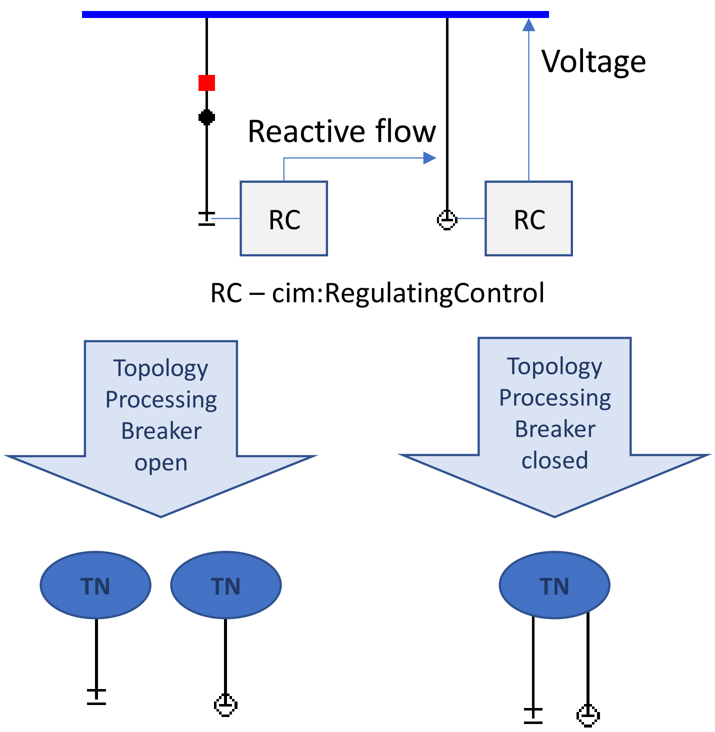


Figure 57 Voltage control with shunts and continuous resource

When the synchronous machine in Figure 57 delivers or consumes a large amount of reactive power to maintain the voltage the shunt will change its capacitance or reactance to lessen the reactive power from the synchronous machine.

If the reactive power is controlled by switching the shunt, a topology processor will create a separate TN if the shunt is disconnected as shown to the lower left in Figure 57. To get the shunt connected back to the TN with the synchronous machine requires closing the switch and repeated topology processing. As the CGM power flow is TN based, topology processing is not used as discussed in section 14.6. Instead, the following solution is to be used:

- Switches shall not be used to control the shunt impedance and be closed when the shunt is in service, e.g. the shunt breaker in Figure 57 is only used when the shunt is taken out of service.
- Use the cim:ShuntCompensator.sections to control the impedance where cim:ShuntCompensator.sections=0 means zero admittance. For linear shunt this means multiplying with the per section admittance results in zero impedance. For nonlinear shunts the cim:NonlinearShuntCompensatorPoint.sectionNumber=0 shall have the corresponding admittance values equal zero.

This is clarified in CGMES v3. There is no section 0 for nonlinear shunt compensator as each of the points provide a value. To model 0 compensation, section 1 should be having 0 values.

14.18 Series compensators

Series compensators may appear both in a substation and somewhere along a transmission line. Modelling a series compensator along a line can be made in two ways:

1. Implicit by adding the series reactance to the cim:ACLineSegment impedances.
2. Explicit by adding the series compensator as a cim:SeriesCompensator together with other equipment that is typically present, e.g. breakers and disconnectors. This require a cim:Substation at the location of the cim:SeriesCompensator.

14.19 Power Transformers

For two winding transformers both series and shunt elements are reactive which means that the series element shall be positive and the shunt element negative. But for equivalenced or three winding transformers a shunt element (cim:PowerTransformerEnd.b) could be positive. If a cim:PowerTransfomer is included as an equivalenced cim:PowerTransfomer the cim:Equipment.aggregate flag shall be true and shunt elements could be positive.

The electrical equivalent of a two winding transformer is an L-model, see Figure 58.

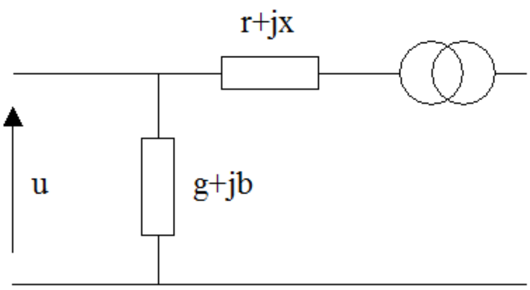


Figure 58 Two Winding Power Transformer L-model (figure copyrighted by IEC)

As can be seen from Figure 58 the model has one shunt and one series element. But the CIM information model has two cim:PowerTransformerEnd-s that can store one shunt and one series element each. To avoid ambiguity it has been decided to store the impedances at the high voltage cim:PowerTransformerEnd which is also end number 1. The other end shall have zero impedance values.

The equivalent model for a three winding transformer is L-elements in a Y-configuration where the shunt elements are at the cim:PowerTransformer cim:Terminal-s. In this case the three pairs of impedance elements are stored in each of the three cim:PowerTransformerEnd-s. As the shunt impedance is typically measured at one of the transformer windings, the shunt impedance should be stored in this cim:PowerTransformerEnd rather than being distributed over all three, see also Figure 59.

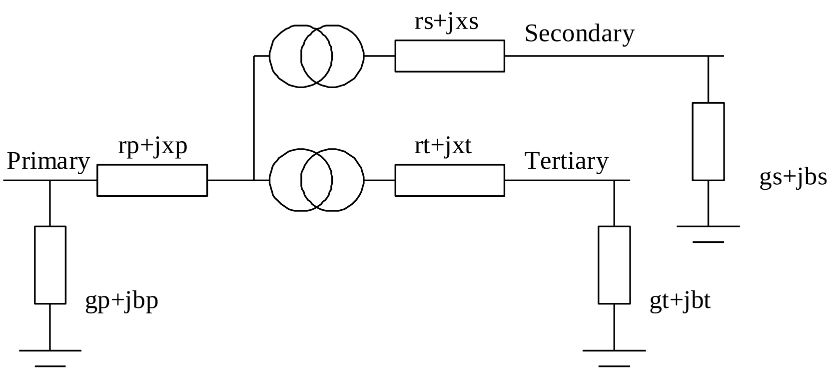


Figure 59 Three Winding Power Transformer L-model (figure copyrighted by IEC)

14.20 Reactive limits

The reactive limits of equipment that can supply reactive power (e.g. cim:SynchronousMachine, cim:EquivalentInjection) is either described by a pair of min/max limit attributes or a reactive capability curve. If a reactive capability curve is present any provided min/max limit attributes shall be ignored.

14.21 Not used classed and attributes

All classes, roles and attributes not described in a profile shall be ignored and reported for diagnostics. Annex E provides some information on not applicable classes and attributes.

14.22 Sign conventions

Table 7 summarizes sign conventions used.

Table 7 Sign conventions

Context	Condition	Sign convention
Market schedule	Domain	Describe an area importing or exporting power. Type of areas are AC net position (EIC type Y) and tie flows (EIC type T) The values are always positive.
Market schedule	in_Domain	Importing domain.
Market schedule	out_Domain	Exporting domain
Market schedule	Power flow on tie-line connectingLine_RegisteredResource	Export and import given by in_Domain and out_Domain
Network model SSH	Net position for ControlArea of type ControlAreaTypeKind.Interchange. The net position is given by ControlArea.netInterchange.	Export has positive value. Import has negative value. (from IEC 61970)
Network model SSH	Equipment injections	Load sign convention is used, i.e., positive sign means flow out from a node (bus) into the equipment.
Network model SSH	Injection by EquivalentInjection at boundary side of branch with TieFlow	Export has negative value. Import has positive value.
Network model SV	SvPowerFlow (AC only)	Load sign convention is used, i.e., positive sign means flow out from a TopologicalNode (bus) into the conducting equipment (from IEC 61970).
Network model SV	SvPowerFlow at boundary side of branch with TieFlow.	Export has positive value. Import has negative value.
Network model SV	SvPowerFlow at EquivalentInjection at boundary side of branch with TieFlow.	Export has negative value. Import has positive value.

The market concept Domain is represented by the network concept ControlArea of type

ControlAreaTypeKind.Interchange.

The net position (ControlArea.netInterchange) is computed by summing up the Domains (in_Domain or out_Domain) linked to a cim:ControlArea.

A market tie flow, having a EIC code of type T, is assigned to the EquivalentInjection linked to the boundary node within a cim:Line having an EIC matching the market tie flow identified by the connectingLine_RegisteredResource.

Annex A HVDC related attributes relevant for CGMES v2.4 (informative)

The tables in this section list the attributes from IEC TS 61970-600:2017 that are normally exchanged in an HVDC IGM. No attributes from IEC 61970-600:2021 are included in this summary.

The column Exchanged in the following tables has the following meaning:

“yes” - the attribute shall always be exchanged except if not used, see Table 16, Table 17 and

- Table 18
- “optional” - the attribute can be included in an export but will not be used in CGM BP.
- “no” - The attribute shall not be included in an exchange.

Table 8 ACDCConverter class

Attribute name	Exchanged	Profile	Comment
baseS	yes	EQ	
idleLoss	yes	EQ	
maxUdc	yes	EQ	
minUdc	yes	EQ	
numberOfValves	yes	EQ	This attribute is 6 for a 6-pulse and 12 for a 12-pulse ACDCConverter.
ratedUdc	yes	EQ	
resistiveLoss	yes	EQ	
switchingLoss	yes	EQ	
valveU0	no	EQ	
p	yes	SSH	
q	yes	SSH	This value shall be approximately p/2 for a current source converter.
targetPpcc	yes	SSH	This value shall agree with p at the rectifier and is used with the control modes CsPpccControlKind.activePower or VsPpccControlKind.pPcc control. Load sign convention is used.
targetUdc	yes	SSH	This value shall agree with udc at the inverter and is used with the control mode CsPpccControlKind.dcVoltage or VsPpccControlKind.udc.
poleLossP	yes	SV	
idc	yes	SV	
udc	yes	SV	
uc	yes	SV	

Table 9 ACDCConverterDCTerminal class

Attribute name	Exchanged	Profile	Comment
polarity	yes	EQ	

Table 10 CsConverter class

Attribute name	Exchanged	Profile	Comment
maxAlpha	optional	EQ	Shall not be used in CGM BP
maxGamma	optional	EQ	Shall not be used in CGM BP
maxIdc	yes	EQ	
minAlpha	optional	EQ	Shall not be used in CGM BP
minGamma	optional	EQ	Shall not be used in CGM BP
minIdc	yes	EQ	
ratedIdc	yes	EQ	
operatingMode	yes	SSH	The rectifier delivers active power to the inverter. This is the case for both current and voltage source converters.
pPccControl	yes	SSH	The control mode CsPpccControlKind.activePower is used for the rectifier and CsPpccControlKind.dcVoltage for the inverter.
targetAlpha	optional	SSH	Shall not be used in CGM BP
targetGamma	optional	SSH	Shall not be used in CGM BP
targetIdc	optional	SSH	Shall not be used in CGM BP
alpha	optional	SV	Shall not be used in CGM BP
gamma	optional	SV	Shall not be used in CGM BP

Table 11 DCConverterUnit class

Attribute name	Exchanged	Profile	Comment
operationMode	yes	EQ	

2503 **Table 12 DCSeriesDevice class**

Attribute name	Exchanged	Profile	Comment
inductance	optional	EQ	Shall not be used in CGM BP
resistance	yes	EQ	
ratedUdc	optional	EQ	Not required as the rated voltage is specified for the converter

2504 **Table 13 DCShunt class**

Attribute name	Exchanged	Profile	Comment
capacitance	optional	EQ	Shall not be used in CGM BP
resistance	yes	EQ	
ratedUdc	optional	EQ	Not required as the rated voltage is specified for the converter

2505 **Table 14 VsConverter class**

Attribute name	Exchanged	Profile	Comment
maxModulationIndex	optional	EQ	Shall not be used in CGM BP
maxValveCurrent	no	EQ	
droop	optional	SSH	Shall be exchanged if the pPccControl mode is pPccAndUdcDroop
droopCompensation	no	SSH	Decided not to use because the PccTerminal is always the controlled point
pPccControl	yes	SSH	The control mode VsPpccControlKind.pPcc is used for the rectifier and VsPpccControlKind.udc for the inverter.
qPccControl	yes	SSH	Only the control mode VsQpccControlKind.voltagePcc is used.
qShare	yes	SSH	Used in voltage control to share the reactive power injection between converters operating in parallel, a voltage droop.
targetQpcc	optional	SSH	This value is used with the control mode VsQpccControlKind.reactivePcc. Load sign convention is used.
targetUpcc	yes	SSH	This value is used with the control mode VsQpccControlKind.voltagePcc.
delta	optional	SV	Shall not be used in CGM BP
uc	optional	SV	Shall not be used in CGM BP

Table 15 DCLineSegment class

Attribute name	Exchanged	Profile	Comment
capacitance	no	EQ	
inductance	no	EQ	
resistance	yes	EQ	
length	no	EQ	

Table 16, Table 17

Table 18 summarizes the control modes for a CsConverter and a VsConverter. The top row in each table list attributes from the CsConverter and VsConverter classes including attributes inherited from the ACDCConverter class. The left most column list the control modes. A dash in the table means the attribute is not used. Rectifier of Inverter refer to the converter operating mode. Some rows contain dashes only which means this control mode is not used. Some columns also contain dashes only which means this attribute at the top row is not used.

Optional attributes (see Table 8 to Table 15) with dashes need not be exchanged.

Table 16 CsConverter active power control modes

operatingMode	targetPpcc	targetUdc	targetIdc	targetAlpha	targetGamma
pPccControl	Rectifier	-	-	-	-
dcVoltage	-	Inverter	-	-	-
dcCurrent	-	-	-	-	-

Table 17 VsConverter active power control modes

pPccControl	targetPpcc	targetUdc	droop
pPcc	Rectifier	-	-
udc	-	Inverter	-
pPccAndUdcDroop	Rectifier	-	Rectifier
pPccAndUdcDroopWithCompensation	-	-	-
pPccAndUdcDroopPilot	-	-	-

2520 **Table 18 VsConverter reactive power control modes**

qPccControl	targetUpcc	targetQpcc	qShare
reactivePcc	-	-	-
voltagePcc	Rectifier/Inverter	-	Rectifier/Inverter
powerFactorPcc	-	-	-

2521

Annex B Proposed changes to CIM/CGMES (informative)

Based on the discussion in this document the following changes to the CIM standard are suggested. It should be noted that some of these issues are covered by the ENTSO-E Network Codes profiles. However further analysis is necessary when packaging then next version of CGMES and IEC standards.

3. Add a new class that describes an HVDC Link.
4. Add a new class that describes an HVDC Pole. The class is contained by an HVDC Link and associates with the DCConverterUnit-s in the HVDC Pole. The boundary points, currently in cim:Line, move into the new HVDC Pole class.
5. To avoid the cases where substations need to be split in two where one is fictitious, may be avoided by moving the substations into the boundary. A single substation can the contain equipment from both the AC and DC IGMs.
6. DC switches are specified in EQ profile, but they do not have an SSH attribute (neither in CGMES 2.4 nor in v3) to state if they are open or closed specified. Temporary solution to this issue is ignoring the DC switches and just using the topology from the TP file as it is. ENTSO-E Network codes extensions and profiles fix this issue.
7. Add a new class that allocates filters for compensating reactive power at current source converters and filter harmonics. The class need an association with the cim:RegulatingControl that have the shunts. The filter control function that allocates filters will use this class depending on the need for harmonics filtering. It use the cim:RegulatingCondEq.controlEnabled flags tell the voltage control which filters are available for voltage control.
8. If the filter control function is located at the DC side of the boundary it needs a path from the cim:ACDConverter to the cim:Regulating control doing the voltage control. This result in restrictions on the cim:ACDConverter.PccTerminal and cim:RegulatingControl.Terminal to be at cim:Teminals linked to the boundary points. This can be avoided if the filter control function is at the AC side.
9. The cim:ACDCConverter class currently serve two purposes 1) describe the control parameters 2) define the electrical connectivity by inheriting cim:ConductingEquipment. It is suggested that the cim:ACDCConverter class only describes the connectivity as indicated Figure 23 and Figure 24. The bridges are not explicitly modelled and may be added if needed in the future, e.g. in dynamics studies. The control parameters could be described by a new class CSControl that replaces CsConverter and VSControl that replaces VsConverter. The new classes represent the “converter unit control” boxes in Figure 18.
10. The BPPL requirements section in IEC 61970-600-1 is suggested to be updated as discussed below
    g) BBPL6 states that “In the simplified exchange of an HVDC link the net interchange between the IGMs is represented by EquivalentInjection classes referring to each common coupling node (CC)”. This is also true for detailed HVDC models which is suggested to be made explicit. The point of common coupling for a cim:ACDCConverter is a cim:Terminal which can be any cim:Terminal. It shall be the cim:Terminal at the cim:EquivalentInjection connected to the boundary point.
    h) BPPL8 states that a detailed HVDC model may be exchanged as a separate IGM or included in the AC IGM. The detailed HVDC model shall always be exchanged as a separate detailed DC IGM that cannot be part of the AC IGM. A simplified HVDC model is described in the AC IGMs without the DC IGMs. A detailed HVDC link is described by also including the DC IGM in a CGM. This is done regardless of an HVDC link is internal or external. See also section 12.1.4.

i) BPPL9 states that the DC IGM shall refer to the common coupling points in the boundary set. The point of common coupling is a cim:Terminal referenced by ACDCConverter. CGM BP requires that this is a branch cim:Terminal connected to the boundary point.

j) BPPL10 states that multiple HVDC Links may be included in a DC IGM. CGM BP requires that each DC IGM can only contain one HVDC link but an HVDC link may contain multiple poles meaning that multiple DC cables and converters are included.

11. ACDCConverter.switchingLoss documentation says, “Switching losses, relative to the base apparent power 'baseS'.” but in the formula for computing the loss it is multiplied by ACDCConverter.idc. The text need check and correction.
12. The description of the VsConverter.droop attribute may be improved, the “D” in the formula need clarification. The VsConverter droop attributes relate to active power which is needed for DC networks. This must be clearly described.
13. Droop control of voltage is common for VsConverters but attributes supporting this is missing in CIM and needs to be added.
14. The description of the VsConverter.targetPhasePcc and VsConverter.targetPWMfactor attributes are left out from the CGM BP. The attributes need clarification and discussion of the relevance in power flow calculations.
15. An information model that describes the party responsible for a shared resource is needed, e.g., two TSOs that have a joint HVDC Link.
16. Figure 38 in IEC 61970-301 does not describe the desired boundary configuration for an HVDC Bipole and it is suggested the figure is replaced.
17. The formula for the pole loss is showed in the ACDCConverter.poleLossP attribute but it would be good to have it at a more prominent place, e.g., in the 301 text.
18. A formula that describes the curve in Figure 25 shall be added. The curve is a function of active power transfer at a given firing or extinction angle and is simple at a fix angle. The approximation Q=P/2 is a last resort that is always available.
19. Add that generation sign convention is used for ACDCConverter.maxP and ACDCConverter.minP
20. Add new classes that describe the bridge and the valves. The lack of a bridge class has resulted in confusion with the ACDCConverterUnit that instead has been used to represent the bridge. As the ACDCConverter unit represents the control of one side of an HVDC Pole rather than the bridges the description in the class need update.
21. The enumeration values activePower, dcVoltage and dcCurrent in CsPpccControlKind need to be investigated as they are probably related to different levels of control. The activePower relate to the whole HVDC Pole while dcVoltage and dcCurrent relate to each CsConverter in the HVDC Pole.
22. The enumeration values of VsPpccControlKind need also be investigated for the same reason. The VsQpccControlKind.pulseWidthModulation is probably a lower-level control that shall not be mixed with the reactePower or voltage controls.
23. Text and diagrams in the HVDC section of IEC 61970-301:2020 are not aligned on parameter naming and the mathematical model describing the static power flow model need better explanation.
24. The control function that describes the dc Voltage at the CSC inverter as a function of transferred power need to be described in the standard. More parameters are probably needed in the UML for this. If the function is complex, it may be described tabularly instead, this also requires a UML change. The function is described in the dynamics model and may be derived from it.

25. The control function that describes the firing/extinction angles and tap position as a function of a dc Voltage target is needed. More parameters are probably needed in the UML for this. If the function is complex, it may be described tabularly instead, this also requires a UML change. The function is described in the dynamics model and may be derived from it.
26. A VsConverter link may have an operation mode where the link exhibits a variable series impedance to the AC system. This require that the series impedance r and x values be dynamically computed and are made available to power flow as attributes. The formulas for computing the r and x values need to be defined.
27. Has the linear loss term in the VSC loss equation the same value as the quadratic?
28. If more than one VSC controls the AC voltage, the attribute VsConverter.qShare tells how the reactive injection shall be shared between the VSCs. This is not clear from the description. The attribute VsConverter.qShare is used with the control mode VsQpccControlKind.voltagePcc which could also be clarified. If multiple VSCs are connected to the AC substation it is assumed that they shall have the same reactive power control mode and the same target values but may have different VsConverter.qShare. This need also be described. Possibly could a RegulatingControl be used to provide common voltage targets would be a change in future CIM versions. In the case other reactive sources are used to control the same voltage a method to share the reactive production between the sources is needed, e.g., the SVC use droop control for this. As HVDC Poles, at least today, are operated at the same bus in the AC system, the bus split issue with RegulatingControl is not an issue for HVDC.
29. Variable impedance control mode is not supported in CIM and needs to be added in future versions, see also section 13.1.2.
30. The HVDC Bipole need to be described. An HVDC Bipole contains two HVDC Poles and has a control function that coordinates the two HVDC Poles. A solution is to describe it with a HVDC Bipole class that will then be contained by the HVDC Link. See also items 1 and 2.

With the CSC filters in the AC IGM it is then easy for the filter control function to reserve and release the filters, e.g. by changing the cim:RegulatingCondEq.controlEnabled flags. If the filter control function is located in the DC Substation the cim:RegulatingControl using filters for voltage control shall also be in the DC Substation. If this is not the case the filter control function and the cim:RegulatingControl will be in different IGMs which means that references will be cross IGMs rather than via the boundary. This in turn breaks the requirement that IGMs shall only depend on the boundary, not each other.

Filter control could be solved by adding the following new classes:

- CSCFilterControl that describe the inputs, outputs and parameters in the control function. The class is made a subtype of cim:Curve.
- CSCFilters that refer to the filters used at a given level of active power transfer. The class is a subclass of CurveData
- An association between CSCFilterControl and cim:RegulatingControl.

Annex C HVDC in IEC 61970-600 (informative)

IEC 61970-301:2020 Edition 7 and IEC 61970-600 have made changes to the HVDC information model from IEC 61970-301:2016 Edition 6. The changes are described in this annex.

To investigate the possible advantage of using the modelling improvement made in IEC 61970-600:2021 HVDC information model rather than using the IEC TS 61970-600:2017 HVDC information model. Most improvements in IEC 61970-600:2021 are descriptions that better aid the understanding of classes, attributes, and roles. Some improvements are additional restrictions on data which are important for implementations.

The DC information model from IEC 61970-600:2021 will not be used in CGM BP which makes this annex out of scope for CGM BP. But the annex is kept as a recording of work done based on the judgement that might still be useful as input to future improvements and for the purpose of completeness.

The DC changes in IEC 61970-301:2020 Edition 7 and IEC 61970-600 are listed in tables below and the column “Incl” stands for include in the CGM BP implementation. A “Yes” in the column means the change shall be included and added as a business process rule and restriction to the IEC TS 61970-600 based information model used for CGM BP. A “No” in the “Incl” column means that the attribute is not used in power flow and need not be exchanged for the current scope of CGM build process.

The tables below describe the information that shall be used in implementations, as a result of detailed analysis, for the purpose of steady state analysis and power flow.

The “Prfl” column indicates the profile.

2668 **Table 19 ACDCConverter class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
baseS	Description extended	The attribute shall be a positive value.	EQ	Yes
idleLoss	Description extended	The attribute shall be a positive value.	EQ	Yes
maxUdc	Description extended	The attribute shall be a positive value.	EQ	Yes
minUdc	Description extended	The minimum voltage on the DC side at which the converter should operate. It is converters configuration data used in power flow. The attribute shall be a positive value.	EQ	Yes
poleLossP	Description extended	The attribute shall be a positive value.	SV	Yes
ratedUdc	Description extended	The attribute shall be a positive value. For instance, a bipolar HVDC link with value 200 kV has a 400kV difference between the dc lines	EQ	Yes
resistiveLoss	Description extended	The attribute shall be a positive value.	EQ	Yes
switchingLoss	Description extended	The attribute shall be a positive value.	EQ	Yes
targetPpcc	Description extended	Load sign convention is used, i.e. positive sign means flow out from a node.	SSH	Yes
targetPpcc	Cardinality change	Optional	SSH	Yes
targetUdc	Description extended	The attribute shall be a positive value.	SSH	Yes
targetUdc	Cardinality change	Optional	SSH	Yes

2669

Attribute/Role	Type of change	Change	Prfl	Incl
uc	Description extended	Line-to-line converter voltage the voltage at the AC side of the valve. It is converters state variable, result from power flow. The attribute shall be a positive value. The attribute shall be a positive value.	SV	No
udc	Description extended	The attribute shall be a positive value.	SV	Yes
valveU0	Description extended	also called Uvalve.	EQ	No
maxP	Added attribute	Maximum active power limit. The value is overwritten by values of VsCapabilityCurve, if present. An active power order shall be below this limit.	EQ	No
minP	Added attribute	Minimum active power limit. The value is overwritten by values of VsCapabilityCurve, if present. An active power order shall be above this limit.	EQ	No
ACDCConverterDCTerminal	Add role descriptions	A DC converter have DC converter terminals. A converter has two DC converter terminals.	EQ	Yes
PccTerminal	Delete text	The power flow measurement must be the sum of all flows into the transformer.	EQ	Yes

2684 **Table 20 ACDCConverterDCTerminal class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
polarity	Description extended	Depending on the converter configuration the value shall be set as follows: - For a monopole with two converter terminals use DCPolarityKind ‘positive‘ and ‘negative‘. - For a bipole or symmetric monopole with three converter terminals use DCPolarityKind ‘positive‘, ‘middle‘ and ‘negative ‘.	EQ	Yes
polarity	Cardinality change	Required	EQ	Yes

2685 **Table 21 CsConverter class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
-	Class description extended	The firing angle controls the dc voltage at the converter, both for rectifier and inverter. The difference between the dc voltages of the rectifier and inverter determines the dc current. The extinction angle is used to limit the dc voltage at the inverter, if needed, and is not used in active power control. The firing angle, transformer tap position and number of connected filters are the primary means to control a current source dc line. Higher level controls are built on top, e.g. dc voltage, dc current and active power. From a steady state perspective it is sufficient to specify the wanted active power transfer (ACDCConverter.targetPpcc) and the control functions will set the dc voltage, dc current, firing angle, transformer tap position and number of connected filters to meet this. Therefore, attributes targetAlpha and targetGamma are not applicable in this case. The reactive power consumed by the converter is a function of the firing angle, transformer tap position and number of connected filter, which can be approximated with half of the active power. The losses is a function of the dc voltage and dc current. The attributes minAlpha and maxAlpha define the range of firing angles for rectifier operation between which no discrete tap changer action takes place. The range is typically 10-18 degrees. The attributes minGamma and maxGamma define the range of extinction angles for inverter operation between which no discrete tap changer action takes place. The range is typically 17-20 degrees.	NA	Yes

alpha	Description extended	Firing angle that determines the dc voltage at the converter dc terminal. The attribute shall be a positive value.	SV	No
gamma	Description extended	It is used to limit the dc voltage at the inverter if needed. Typical value between 17 degrees and 20 degrees for an inverter. The attribute shall be a positive value.	SV	No
maxAlpha	Description extended	The attribute shall be a positive value.	EQ	No
maxGamma	Description extended	The attribute shall be a positive value.	EQ	No
minIdc	Description extended	The attribute shall be a positive value.	EQ	Yes
pPccControl	Description added	Kind of active power control.	SSH	Yes
ratedIdc	Description extended	The attribute shall be a positive value.	EQ	Yes
targetAlpha	Description extended	It is only applicable for rectifier if continuous tap changer control is used. Allowed values are within the range minAlpha<=targetAlpha<=maxAlpha. The attribute shall be a positive value.	SSH	No
targetGamma	Description extended	It is only applicable for inverter if continuous tap changer control is used. Allowed values are within the range minGamma<=targetGamma<=maxGamma. The attribute shall be a positive value.”	SSH	No
targetIdc	Description extended	The attribute shall be a positive value.	SSH	No
CSCDynamics	Association added for DY profile.		DY	No

2686 **Table 22 CsOperatingModeKind class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
inverter	Description extended	which is the power receiving end.	SSH	Yes
rectifier	Description extended	which is the power sending end.	SSH	Yes

2687 **Table 23 CsPpccControlKind class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
activePower	Description changed	Control is active power control at AC side, at point of common coupling. Target is provided by ACDCConverter.targetPpcc.	SSH	Yes
dcVoltage	Description changed	Control is DC voltage with target value provided by ACDCConverter.targetUdc.	SSH	Yes
dcCurrent	Description changed	Control is DC current with target value provided by CsConverter.targetIdc.	SSH	No

2688 **Table 24 DCBaseTerminal class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
DCNode	Description changed	The DC connectivity node to which this DC base terminal connects with zero impedance.	EQ	Yes

2689 **Table 25 DCConductingEquipment class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
ratedUdc	New attribute	Rated converter DC voltage, also called UdN. The attribute shall be a positive value. It is converters configuration data used in power flow. For instance, a bipolar HVDC link with value 200 kV has a 400kV difference between the dc lines.	EQ	No
DcTerminal	Description added	A DC conducting equipment has DC terminals.	EQ	Yes

2690 **Table 26 DCConverterUnit class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
operationMode	Description added	The operating mode of an HVDC Bipole (bipolar, monopolar metallic return, etc).	EQ	Yes
Substation	Description added	The containing substation of the DC converter unit.	EQ	Yes

2691 **Table 27 DCEquipmentContainer class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
DCNode	Description added	The DC nodes contained in the DC equipment container.	TP	Yes
DCTopologicalNode	Description added	The topological nodes which belong to this connectivity node container.	TP	Yes

2692 **Table 28 DCLine class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
Region	Description added	The SubGeographicalRegion containing the DC line.	EQ	Yes

2693 **Table 29 DCNode class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
DCTopologicalNode	Description added	The DC topological node to which this DC connectivity node is assigned. May depend on the current state of switches in the network.	TP	Yes
DCTerminals	Description added	DC base terminals interconnected with zero impedance at a this DC connectivity node.	EQ	Yes

2694 **Table 30 DCPolarityKind class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
positive	Description extended	The converter terminal is intended to operate at a positive voltage relative the midpoint or negative terminal.	EQ	Yes
middle	Description extended	The converter terminal is the midpoint in a bipolar or symmetric monopole configuration. The midpoint can be grounded and/or have a metallic return.	EQ	Yes
negative	Description extended	The converter terminal is intended to operate at a negative voltage relative the midpoint or positive terminal.	EQ	Yes

2695 **Table 31 DCSeriesDevice class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
ratedUdc	Deleted	inherited from: DCConductingEquipment	EQ	No

2696 **Table 32 DCShunt class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
ratedUdc	Deleted	inherited from: DCConductingEquipment	EQ	No

2697 **Table 33 DCTopologicalIsland class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
DCTopologicalNode	Description added	The DC topological nodes in a DC topological island.	TP	Yes

2698 **Table 34 VsConverter class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
delta	Description extended	The attribute shall be a positive value or zero.	SV	No
droop	Description extended Unit changed	The attribute shall be a positive value. modified the unit to PU	SSH	No
droop	Cardinality change	Optional	SSH	No
droopCompensation	Description extended	clarified that it is resistance The attribute shall be a positive value.	SSH	No
droopCompensation	Cardinality change	Optional	SSH	No
maxValveCurrent	Attribute deleted		NA	No
qPccControl	Description added	Kind of reactive power control.	SSH	Yes
qShare	Description extended	The attribute shall be a positive value or zero.	SSH	Yes
qShare	Cardinality change	Optional	SSH	Yes
targetQpcc	Description extended	Load sign convention is used, i.e. positive sign means flow out from a node.	SSH	Yes
targetQpcc	Cardinality change	Optional	SSH	Yes
targetUpcc	Description extended	The attribute shall be a positive value.	SSH	Yes
targetUpcc	Cardinality change	Optional	SSH	Yes
uv	Renamed from uf Description changed	Line-to-line voltage on the valve side of the converter transformer. It is convert's state variable, result from power flow. The attribute shall be a positive value.	SV	No
targetPowerfactorPcc	New attribute	Power factor target at the AC side, at point of common coupling. The attribute shall be a positive value.	SSH	No
targetPhasePcc	New attribute	Phase target at AC side, at point of common coupling. The attribute shall be a positive value.	SSH	No
targetPWMfactor	New attribute	Magnitude of pulse-modulation factor. The attribute shall be a positive value.	SSH	No

VSCDynamics	New role in DY profile		DY	No
maxModulationIndex	No change		SSH	No
maxValvecurrent	No change		EQ	No

2699 **Table 35 VsPpccControlKind class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
pPcc	Description extended	The target value is provided by ACDCConverter.targetPpcc.	SSH	Yes
udc	Description changed	with target value provided by ACDCConverter.targetUdc.	SSH	Yes
pPccAndUdcDroop	Description extended	Target values are provided by ACDCConverter.targetPpcc, ACDCConverter.targetUdc and VsConverter.droop.	SSH	No
pPccAndUdcDroopWithCompensation	Description extended	Targets are provided by ACDCConverter.targetPpcc, ACDCConverter.targetUdc, VsConverter.droop and VsConverter.droopCompensation.	SSH	No
pPccAndUdcDroopPilot	Description extended	The mode is used for Multi Terminal High Voltage DC (MTDC) systems where multiple HVDC Substations are connected to the HVDC transmission lines. The pilot voltage is then used to coordinate the control the DC voltage across the HVDC substations. Targets are provided by ACDCConverter.targetPpcc, ACDCConverter.targetUdc and VsConverter.droop.	SSH	No
phasePcc	New attribute	Control is phase at point of common coupling. Target is provided by VsConverter.targetPhasePcc.	SSH	No

2700 **Table 36 VsQpccControlKind class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
-	Class description added	Types applicable to the control of real power and/or DC voltage by voltage source converter.	SSH	Yes
reactivePcc	Description extended	Control is reactive power at point of common coupling. Target is provided by VsConverter.targetQpcc.	SSH	Yes
voltagePcc	Description extended	Control is voltage at point of common coupling. Target is provided by VsConverter.targetUpcc.	SSH	Yes
powerFactorPcc	Description extended	Control is power factor at point of common coupling. Target is provided by VsConverter.targetPowerFactorPcc.	SSH	Yes
pulseWidthModulation	New attribute	No explicit control. Pulse-modulation factor is directly set in magnitude (VsConverter.targetPWMfactor) and phase (VsConverter.targetPhasePcc).	SSH	No

2701 **Table 37 DCLineSegment class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
capacitance	Cardinality change	Required	EQ	Yes
resistance	Description extended	The attribute shall be a positive value.	EQ	Yes

2702 **Table 38 PerLengthDCLineParameter class changes**

Attribute/Role	Type of change	Change	Prfl	Incl
-	Class deleted		EQ	Yes

2703 **Table 39 BoundaryPoint class changes (not in DC)**

Class/Attribute/Role	Type of change	Change	Prfl	Incl
BoundaryPoint		New class		No
isDirectCurrent	Used in DC		EQ&TP	No
isExcludedFromAreaInterchange	Used in DC		EQ&TP	No

2704 **Table 40 Class rules**

Class	Attribute/Role	Rule	Incl
DCGround	-	At least one DCGround shall be defined for each dc circuit	Yes

Equipment	EquipmentContainer	ProtectedSwitch (Breaker, DisconnectingCircuitBreaker, LoadBreakSwitch) the association shall point to EquipmentContainer of type Bay, Line or DCConverterUnit. SeriesCompensator the association shall point to EquipmentContainer of type VoltageLevel when in substation, DCConverterUnit or Line when outside substation. PowerTransfomer the association shall point to EquipmentContainer of type Substation or DCConverterUnit. Disconnector the association shall point to EquipmentContainer of type Bay, VoltageLevel, DCConverterUnit or Line when outside substation. GroundDisconnector the association shall point to EquipmentContainer of type Bay, VoltageLevel, DCConverterUnit or Line when outside substation. Fuse the association shall point to EquipmentContainer of type Bay, VoltageLevel, DCConverterUnit or Line when outside substation. Jumper the association shall point to EquipmentContainer of type Bay, VoltageLevel, DCConverterUnit or Line when outside substation. Cut the association shall point to EquipmentContainer of type Bay, VoltageLevel or DCConverterUnit or Line when outside substation. DCSwitch (DCDisconnector, DCBreaker) the association shall point to EquipmentContainer of type DCConverterUnit. DCGround the association shall point to EquipmentContainer of type DCConverterUnit. DCBusbar the association shall point to EquipmentContainer of type DCConverterUnit. DCChopper the association shall point to	

		EquipmentContainer of type DCConverterUnit. DCShunt the association shall point to EquipmentContainer of type DCConverterUnit. DCSeriesDevice the association shall point to EquipmentContainer of type DCConverterUnit. DCLineSegment the association shall point to EquipmentContainer of type DCLine. In the case of modelling back to back configuration the association shall point to EquipmentContainer of type Substation. ACDCConverter (CsConverter, VsConverter) the association shall point to DCEquipmentContainer of type DCConverterUnit. In this case the association DCConverterUnit.Substation is required.	
EquivalentInjection		If EquivalentInjection.regulationCapability in EQ is true, then EquivalentInjection.regulationStatus and EquivalentInjection.regulationTarget are required in SSH. If EquivalentInjection.regulationCapability in EQ is false, then EquivalentInjection.regulationStatus and EquivalentInjection.regulationTarget are not exchanged in SSH. If EquivalentInjection connects to a BoundaryPoint with flag isDirectCurrent=false (meaning this is not HVDC), the EquivalentInjection.regulationCapability in EQ shall be set to false and there shall not be a ReactiveCapabilityCurve associated.	

ACDCConverter		The target values and related attributes for ACDCConverter and its subclasses are optional in SSH. However, depending on the control mode of the converter some of the attributes shall be considered as required. The description of the control modes in the enumerations CsPpccControlKind, VsPpccControlKind and VsQpccControlKind provide information on necessary attributes which are then considered required attributes for each control mode in SSH.	

As an advice, when eventually moving from IEC TS 61970-600:2016 [1] to IEC 61970-600:2021 [8] the following changes need attention:

- The attribute ratedUdc that is moved to the base class DCConductingEquipment that means a name change of this attribute in the EQ CIMXML file.

Annex D HVDC Technology (Informative)

The below discussion is based on Figure 20.

The dc current in an HVDC Pole is determined by the voltage difference between the rectifier and inverter, i.e., idcx = (udcx[r]-udcx[i])/Rx. To maintain the power flow from the rectifier to the inverter the inverter keeps a constant voltage udcx[i] and the rectifier controls the dc current by varying the voltage udcx[r]. To accomplish this udcx[r] is bigger than udcx[i] and kept close to ratedUdc. Hence the cim:CsPpccControlKind seem to mix two levels of control as the cim:CsPpccControlKind.activePower relates to the HVDC Pole control while the cim:CsPpccControlKind.dcVoltage and cim:CsPpccControlKind.dcCurrent relates to cim:CsConverter control, see section Annex A for a description of the control modes.

How the dc voltage depends on the ac voltage, tap position and firing/extinction angles is described by the formulas below.

$$U_{DC[rectifier]} = U_{DC0} * cos(\alpha) - \frac{3X_{tr}}{2\pi} I_{DC}$$

$$U_{DC[inverter]} = U_{DC0} * cos(\gamma) - \frac{3X_{tr}}{2\pi} I_{DC}$$

$$U_{DC0} = \frac{3\sqrt{2}}{\pi} * tapratio * U_{AC}$$

Where

- $U_{DC[xxxxxxxx]}$ is cim:ACDCConverter.udc at the rectifier and inverter.
- U_{DC0} is the rated dc voltage
- I_{DC} is the cim:ACDCConverter.idc.
- X_{tr} is the impedance at the transformer including any series reactance.
- α is the firing angle cim:ACDCConverter.alpha.
- γ is the extinction angle cim:ACDCConverter.gamma.
- $tapratio$ is the quotient between the AC voltages at each side of the transformer.
- U_{AC} is the voltage at the AC bus.

To be able to use these formulas the control function determining the firing/extinction angles and tap positions must also be known. The control function uses the firing and extinction angle to change the dc voltage (Udc) and when the limits for these angles are reached the tap position is changed so the angles are moved to middle between the angle limits.

The injected power at the rectifier is P1 = udc1*idc. To compute the power delivered by the inverter we need to subtract all the losses in the HVDC Pole from P1 as showed by the second equation in Figure 19. The losses (Ploss) are a function of Idc as shown by the third equation in Figure 19. To compute Idc we can decide on a value for Udc1. As the losses increase with the square of the current a high value will minimize the losses. For this reason the rated voltage (cim:ACDCConverter.ratedUdc) is used.

An algorithm to compute the transferred power p[i] from the inverter at a given active power sent from the rectifier is

- The active power p[r] at the rectifier is targetPpcc[pole] from the level 2, in this case an HVDC Bipole. The value is picked up from the HVDC Pole schedules for this boundary point.
- Compute the dc current at the rated voltage at given active power transfer at the rectifier

- idc = p[r]/ratedUdc
- Compute the losses at this current
- poleLossP = idleLoss + switchingLoss*|idc| + resitiveLoss* idc^2
- Compute the power delivered by the inverter as p[i] = -(p[r] – poleLossP). This is the value at EI.p at the inverter.

All parameters above are from the cim:ACDConverter, cim:CsConverter or cim:EquivalentInjection.p (EI.p) if nothing else indicated.

The above algorithm put all the losses at the inverter side assuming that the HVDC Pole schedules already considered how the losses are split

Shunt capacity is used keep cos(ϕ) = 1 so that no reactive power is pulled from the AC network. The harmonics filtering has priority over getting cos(ϕ) = 1 which could result in production of more reactive power than consumed by the converter which tend to raise or lower the voltage. Over voltages are reduced by use of shunt reactors or static var compensators.

The reactive power consumed by a current source converter is roughly 45 to 65 percent of the transferred active power. The curve in Figure 25 show how the reactive power consumption typically depends on the active power transfer at fix firing and extinction angles.

Figure 25 in section 12.1.3 show how the reactive power consumption increase more than linearly with increasing active power transfer due to increased current lag resulting in decreasing power factor cos(ϕ). The reactive power consumption is also dependent on the firing and extinction angles as shown in Figure 25. Both angles are kept in a small range which avoids big changes in reactive power consumption due to angle variations, a typical range for the extinction angle is indicated by the dashed lines in Figure 25. Due to this the shunt control needs to switch capacitors or reactors in or out to provide reactive power matching the reactive power consumption, this is regular voltage control. The reactive power consumption by a converter is described by a function Q = q(P). Detailed formulas for q(P) can be found in IEC 61970-301:2020 (Edition 7) and in HVDC literature, e.g., [10]. Assuming that the firing/extinction angles is considered fixed a commonly used simplified formula is Q=P/2 or Q=0.6*P. A better approximation is Q=P*sqrt($(udc/udc0)^2$ -1) where udc is the dc voltage and udc0 is the rated dc voltage.

For a business process where the active power transfer is known but not the reactive power consumption (e.g., 1D and 2D) a formula for computing it is useful.

For a VsConverter the tap changer does not have the same active role in controlling the power transfer as in a CsConverter which means that voltage Uv is stable. This means the angle δ and amplitude of Uc are the two controlled entities. The quotient Uc and Udc amplitudes, called the modulation index, is used to control the Uc amplitude and the reactive power flow.

As the VsConverter active and reactive power control is continuous and decoupled it is simpler to describe for use in power flow calculations than for a CsConverter where converter reactive power consumption and harmonics filtering must be described.

Figure 19 show a complete HVDC Pole for a monopole with metallic ground return. The active power flow across the DCLineSegment follow the same equation as for the CsConverter

- idc = (udc[r] – udc[i])/R where R = cim:DCLinesegment.resistance.
- p[r] = udc[r]*idc = udc[r]* (udc[r] – udc[i])/R

The side sending active power is referred to as the “rectifier” indexed [r] and the side receiving active power as the “inverter” indexed [i].

The sides operate like a CsConverter were

- The sending side in Figure 19 determines the active power flow by controlling the difference udc[r] – udc[i]. As udc[i] is not available the angle δ, that is measured, is used instead.
- The receiving side determines the voltage udc[i].

Each side control their own reactive power exchange with the AC system.

There are numerous ways to create the PWM pulses and how this is done is outside the scope of this document.

The losses are computed the same formula as for CsConverters

- $poleLossP[1] = idleLoss + switchingLoss*|Idc| + resistiveLoss* Idc^2$.

IEC 61970-301:2020 has a formula with an additional linear resistiveLoss term which may be an error.

Annex E Not applicable classes and attributes (Informative)

There are several attributes that are not used but being exchanged in IGMs. Some are defined in the CGMES and some in canonical CIM, which is only applicable for CGMES v2.4. This information is only an example as such information may change over time and cannot be kept up to date. Therefore, the table does not imply restrictions.

Table 41 Not applicable classes or attributes

Attribute	Defined in	Comment
EquivalentBranch.r21 EquivalentBranch.x21	CGMES	The attributes EquivalentBranch.r21 and EquivalentBranch.x21 shall be symmetric, i.e., have the same values as EquivalentBranch.r and EquivalentBranch.x. For this reason, they are not needed and shall not be used.
PhaseTapChangerNonLinear.xMin	CGMES	This attribute is redundant with PhaseTapChangerNonLinear.xMax and shall not be used.
GeneratingUnit.initialP	CGMES	This attribute can be used as a starting point to power flow when no other data is available. The SSH file contains all the needed inputs.
VoltageLevel.highVoltageLimit VoltageLevel.lowVoltageLimit	CGMES	The limits used are from OperationalLimits, these attributes are not used.
EnergyConsumer.pfixed EnergyConsumer.qfixed EnergyConsumer.pfixedPct EnergyConsumer.qfixedPct	CGMES	This attribute can be used to create a starting point to power flow when no other data is available. The SSH file contains all the needed inputs.
SeriesCompensator.varistorPresent SeriesCompensator.varistorRatedCurrent SeriesCompensator.varistorThresholdVoltage	CGMES	These attributes are used for over voltage protection and are not applicable.
ShuntCompensator.switchOnCount ShuntCompensator.switchOnDate	CGMES	These attributes are used for asset health supervision and are not applicable.
BusNameMarker	CGMES	This class is used in node breaker models and topology processing to generate cim:TopologicalNode-s with the same name and ID. Currently not applicable but may be in the future.

Attribute	Defined in	Comment
Meas package classes Accumulator, AccumulatorLimit, AccumulatorLimitSet, AccumulatorReset, AccumulatorValue, Analog, AnalogLimit AnalogLimitSet, AnalogValue, Command Discrete, DiscreteValue, MeasurementValueQuality, MeasurementValueSource, RaiseLowerCommand, SetPoint StringMeasurement, StringMeasurementValue ValueAliasSet, ValueToAlias	CGMES	These attributes are used to describe measurements, e.g., in a SCADA/EMS, and are not applicable.
Pattern data Season, DayType, ConformLoadSchedule, NonConformLoadSchedule, RegulationSchedule, SwitchSchedule TapSchedule	CGMES	These classes are used to set up power flow inputs, e.g., loads and switch position. Not applicable as this information is already in the SSH. In the future they could be used to support creation of SSH.
Junction	CGMES	This class is currently used in the boundary in case geographical location information is needed. In CGMES v3 the class is no longer needed as locations are managed by the new class BoundaryPoint. The class shall not be used.
Real time operational information OperatingParticipant OperatingShare, ReportingGroup	CGMES	The use of these classes is not well defined. Some use them as a way to determine joint operational responsibilities, not applicable.