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Use of CIM models, based on IEC 61970 Standards, for information exchange in HVDC Digital Twins systems

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ABSTRACT Digital twins are emerging as transformative tools for High Voltage Direct Current (HVDC) transmission systems, enabling real-time monitoring, predictive maintenance, and operational optimization. However, the effectiveness of these virtual replicas fundamentally depends on seamless, reliable data exchange with their physical counterparts and any other support system.
The current landscape of HVDC digital twin implementations reveals a critical challenge: the absence of standardized data exchange protocols leads to vendor lock-in, interoperability issues between data provided by different vendors, and increased lifecycle costs. This paper argues for the adoption of standardized data exchange methodologies in HVDC digital twins and examines the suitability of the Common Information Model (CIM) defined in IEC 61970 as a foundation for this standardization, an established and proven data structure for electrical systems that also includes HVDC elements.

INDEX TERMS CIM model, HVDC, Digital Twin, IEC 61970, IEC 61850

I. INTRODUCTION

HVDC plants can incorporate equipment from multiple vendors, each employing proprietary data formats and communication protocols. Digital twins must interface with diverse systems including Supervisory Control and Data Acquisition (SCADA), converter control systems, valve monitoring systems, and protection devices, plus other management tools. Without standardization, each interface requires custom development, creating several critical problems:

- Integration Complexity: Custom interfaces between digital twins and physical systems require extensive engineering effort, specialized knowledge of proprietary protocols, and ongoing maintenance as systems evolve. This complexity multiplies when digital twins must integrate data from multiple HVDC projects or vendors.
- Scalability Limitations: As HVDC networks expand globally, the ability to replicate and scale digital twin implementations across multiple facilities becomes essential. Proprietary approaches create barriers to scaling, requiring re-engineering for each new plant or technology upgrade.
- Lifecycle Management Risks: HVDC facilities operate for decades, often outlasting the original equipment vendors' support lifecycles. Proprietary data exchange methods create long-term dependencies and vulnerabilities when vendors discontinue products or modify their data structures.

The economic case for standardization is also interesting. Industry studies indicate that data integration consumes an important part of digital twin implementation budgets [1]. Standardized interfaces can dramatically reduce these costs through reusable components, reduced testing requirements, and faster deployment cycles. Furthermore, standardization enables competitive markets for digital twin solutions, preventing monopolistic pricing structures that emerge from vendor lock-in. From a technical perspective, standardized data exchange enables advanced applications that span multiple facilities or integrate HVDC systems with broader grid operations. Multi-terminal HVDC systems, HVDC grids, and hybrid AC/DC networks require coordinated digital representations that can only be achieved through common data semantics and exchange mechanisms.

This report proposes the use of the Common Information Model (CIM) for High-Voltage Direct Current (HVDC) digital twins, specifically within the context of the IEC 61970 series of standards. It emphasizes the crucial role of CIM in facilitating seamless data exchange and ensuring interoperability among the diverse range of applications and systems operating within HVDC stations and links.

The Common Information Model defined in IEC 61970 offers a mature, proven framework particularly well-suited for this standardization. Its semantic comprehensiveness, established interoperability mechanisms, and alignment with broader power system modeling practices make it an ideal foundation for HVDC digital twin data exchange. While implementation requires careful attention to HVDC-specific requirements and thoughtful architectural design, the benefits—reduced costs, enhanced interoperability, and future-proofed systems—strongly justify the adoption of CIM-based approaches.

As the HVDC industry continues its rapid growth and digital twins become increasingly central to plant operations, the establishment of standardized data exchange methodologies should be recognized as a strategic objectives.

The remaining sections are structured as follows. Section II describes which are the basis concepts for IEC 61970/CIM. Section III details the interaction between CIM model and IEC 61850 standard. Section IV explains why the CIM models the best option for structuring data in HVDC stations digital twins. Finally, Section V presents the conclusions of this paper.

II. CIM/IEC 61970: A FOUNDATION FOR HVDC DIGITAL TWIN DATA EXCHANGE

The objectives of the CIM models are to enable the utilization of plug-compatible applications and to safeguard the investments made by utilities in these applications. By establishing standardized data interfaces between different software systems, CIM enables utilities to integrate new applications from diverse vendors with significantly less effort and errors dedicated to data integration. CIM plays a vital role in simplifying data integration and lowering the overall costs and effort associated with connecting disparate systems [2].

A. WHAT IS THE IEC 61970 STANDARDS FAMILY ?

The Common Information Model (CIM) is an abstract information model designed to represent an electrical network and the various equipment utilized within it.

Originally developed by the North American Electric Reliability Corporation (NERC) in the United States to handle the exchange of data in the transmission level of the power system, due to the reasons mentioned before, not it stands as an open standard, developed and maintained collaboratively by the electric power industry, and has been officially adopted by the International Electrotechnical Commission (IEC), under the standard family IEC 61970 series, growing to a much more complex and comprehensive model now used by companies along the world, from the European Network of Transmission System Operators for Electricity (ENTSO-E) in Europe to many utilities in Asia.

The IEC 61970 series, developed by the International Electrotechnical Commission, defines the Common Information Model for energy management systems, providing a comprehensive semantic framework for representing power system components, their relationships, and operational data. Originally focused on AC transmission systems, CIM has evolved to include diverse power system elements from distribution to transmission, including support to HVDC systems.

Initially, CIM found widespread use in facilitating data exchange for bulk transmission power systems. However, its application is now increasingly extending to include distribution modeling and analysis. This broadening scope reflects the growing recognition of the need for standardized data management across all voltage levels of the power system. The increasing integration of distributed generation and the deployment of smart grid technologies have amplified the importance of a unified approach to data handling in these evolving networks.

It is vital to recognize that CIM is fundamentally a semantic model [3] [4]. As such, it provides an abstract and formal depiction of power system objects, their inherent attributes, the relationships that bind them, and the operations that can be performed upon them. CIM should not be confused with a database structure or a physical data store. Instead, it functions as a common vocabulary for describing power system data in a manner that is independent of any specific implementation or underlying storage mechanism.

B. THE ROLE OF IEC 61970 STANDARDS

The IEC 61970 series of standards specifically (Fig. 1) addresses the application program interfaces (APIs) for energy management systems (EMS). These standards offer a comprehensive set of guidelines and specifications designed to facilitate the seamless integration of applications developed by various suppliers. Furthermore, they enable the efficient exchange of information with systems located external to the control center environment.

The IEC 61970 series is structured into several key parts to address different aspects of EMS-API and information modeling:

- **Part 1:** Outlines the general guidelines and requirements necessary for the application of the EMS-API interface standards.
- **Part 2:** Provides a comprehensive glossary of terms used throughout the IEC 61970 series.
- **Part 3XX:** Focuses specifically on the Common Information Model (CIM), defining the abstract model and its various components.
- **Part 4XX:** Details the Component Interface Specification (CIS), which describes the standard interfaces for information exchange.

- **Part 5XX:** Specifies the technology mappings for the CIS, outlining how the abstract interfaces are implemented using specific technologies.

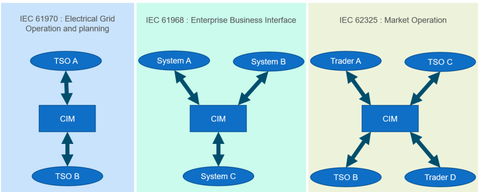

FIGURE 1. IEC61970 family [5]

The parts of the IEC 61970 series most directly relevant to the CIM fall within the 61970-3XX range. These sections are dedicated to defining the CIM base model and other logical views of the power system. The core of the CIM is established in **IEC 61970-301**, officially titled "Energy management system application program interface (EMS-API) - Part 301: Common information model (CIM) base". The most recent version of this standard is IEC 61970-301:2020 (Edition 7.0), which incorporates significant technical enhancements, including the addition of ICCP configuration modeling functionalities. Beyond the base model, other crucial standards within the IEC 61970 series extend the CIM to cover specialized areas. These include **IEC 61970-302** (CIM Dynamics), which addresses the modeling of dynamic system behavior, **IEC 61970-452** (CIM Static Transmission Network Model Profiles), which defines profiles for static network representations to execute state estimation and power flow applications, and **IEC 61970-457** (Dynamics Profile), which specifies a standard interface for exchanging dynamic model information needed to support the analysis of the steady-state stability (small-signal stability) and/or transient stability of a power system or parts of it. These extensions demonstrate how the fundamental CIM base model is adapted and expanded to address the specific requirements of various functionalities and domains within power systems.

The IEC standard 61970-301 is a semantic model that describes the components of a power system at an electrical level and the relationships between each component.

The point of the IEC 61970/61968 standards is to support the integration of applications or devices from different vendors. In general, three types of integration-based standards can be viewed:

1) Standards focusing on syntactic interoperability, providing descriptions for interfaces.
2) Standards focusing on semantic interoperability, which provide a common semantic data model in addition to syntactic interoperability.
3) Plug-and-play standards, the ideal form of standards, which do not require additional customization and with applications providing specified interfaces, successful exchange of data can be achieved.

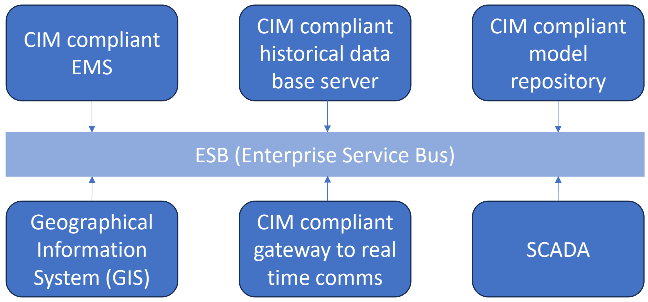

FIGURE 2. Communication architecture based on Enterprise Service Bus (ESB)

C. CIM MODELS AND INTEROPERABILITY

A fundamental motivation behind the development and widespread adoption of CIM in the power industry is the critical need to achieve seamless interoperability among the applications and systems that are essential for the operation and management of modern power grids.

Interoperability, in this context, signifies the capability of different hardware and software components, often from various vendors and serving diverse functions, to connect, communicate, and exchange data effectively. CIM serves as a key component in this endeavor by providing a standardized semantic framework that enables a common understanding of power system data across these heterogeneous systems and domains.

CIM facilitates this seamless communication and data exchange between systems that may have vastly different underlying data models. This is frequently accomplished through the use of CIM adapters, specialized software components that translate data from a system's native format into the standardized CIM format, and vice versa. Furthermore, Enterprise Service Buses (ESBs) are often employed as central communication infrastructures 2 that facilitate the routing and exchange of CIM-based messages between various applications, thereby simplifying complex integration scenarios.

D. KEY COMPONENTS AND FUNDAMENTAL CONCEPTS OF CIM

The CIM is primarily defined and represented using the Unified Modeling Language (UML), a standardized graphical language that allows for the clear and precise depiction of the structure and behavior of entities within power systems. UML facilitates the definition of fundamental concepts such as:

- **classes**, which are abstractions that describe tangible and abstract elements of the power system (for instance, transformers, transmission lines, ...) [6],
- **attributes**, which describe the inherent properties of these classes (like voltage rating, line impedance, ...).
- **relationships**, which illustrate how these classes are interconnected and interact with one another (e.g., a transformer is connected to a transmission line, ...), being main types the associations, aggregations and

multiplicities. The `domain` is the source class of the relationship, while the `range` is the target class, while the `multiplicity` defines how many instances of the domain/range class can be related to one instance of the other class.

e.g. In the association between Breaker and Terminal, the breaker is the domain, while the terminal is the range, with a multiplicity of 2, So 1 breaker is associated with 2 terminals

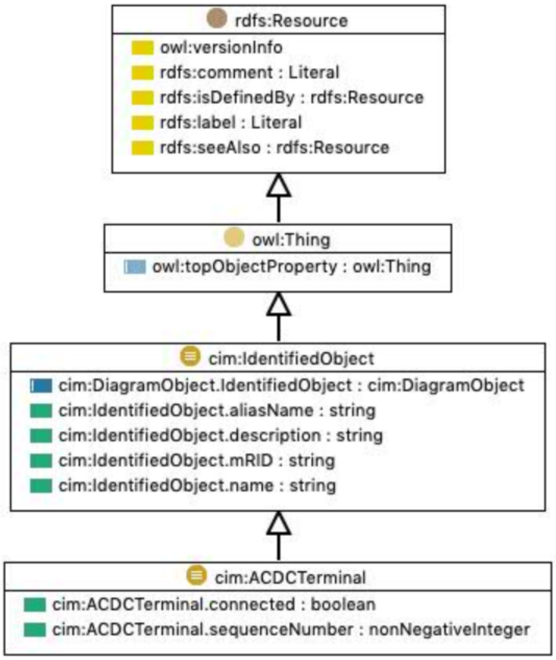

FIGURE 3. **CIM's ACDCterminal class [7]**

One of the basis of the CIM's structure is the principle of **inheritance**, a powerful feature of UML where more specialized classes automatically acquire the properties and behaviors of more general classes. This hierarchical arrangement allows for a more efficient and organized representation of power system components. For example, in the CIM, a `Breaker` is defined as a specific type of `ProtectedSwitch`, which in turn is a specialized form of a more general `Switch`. This inheritance mechanism promotes code reuse and facilitates a more intuitive understanding of the relationships between different power system elements.

The CIM framework is logically organized into several key **packages**, each serving to group related concepts and functionalities. These packages include:

- `Core` which contains the building block classes common to all applications
- `Wires` which defines the electrical characteristics of various equipment
- `Domain` which specifies the primitive data types used throughout the model

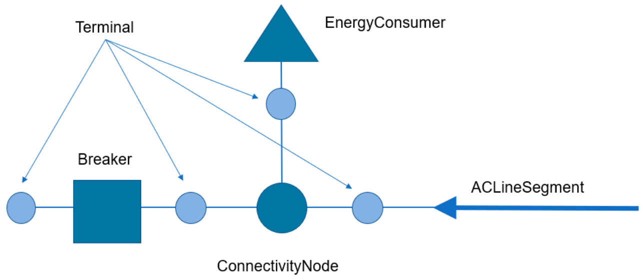

FIGURE 4. **Circuit representation example, including the terminals**

- `Assets` which describes the physical attributes of tangible utility resources;
- `AssetInfo` which holds asset-specific descriptive information.

To accurately model the physical connections between components within the power system network, the CIM employs the concepts of **Connectivity Nodes** and **Terminals**. Physical equipment, such as circuit breakers and power transformers, are represented as `ConductingEquipment` and possess one or more `Terminals`. These terminals serve as the points of connection to `Connectivity Nodes`, which represent locations within the network where the terminals of multiple conducting equipment meet, assumed to have zero impedance. This concept is fundamental to defining the topology of the electrical network within the CIM.

Class diagrams show all the attributes and associations of various classes in a particular package. Objects specified using CIM inherit all the attributes and associations of their parent classes. CIM classes also inherit all of the associations of their parent classes to other classes. The highest-level class of objects in CIM is called IdentifiedObject. This class is very abstract and only contains attributes used to reference the object either by a user or in software. One of the most important attributes of IdentifiedObject is the master resource identifier (mRID), which is a globally unique 3- to 18-character identifier of objects; the mRID does not have to be human-readable. It is strongly recommended that this identifier be a Universally Unique Identifier (UUID) [8]. This ensures that different software systems and applications that exchange CIM data can refer to the same power system component without any possibility of confusion or misinterpretation. The mRID plays a vital role in facilitating accurate data integration and seamless interoperability across various platforms and systems.

All elements of the power system model are categorized as a `PowerSystemResource`, which can be any item of equipment (e.g., a switch), an equipment container with multiple pieces of equipment (e.g., a substation or a feeder), or an organizational entity (e.g., a control area). All power system modeling components are then divided into two categories, depending on whether the particular focus is on the electrical connectivity or the physical assets. All electrical aspects of equipment are associated with the classes inheriting from the `Equipment` class in the IEC 61970 package. The physical aspects of equipment are associated with the `Assets` and `AssetInfo` packages of the 61968 package [8].

This modular structure not only makes the CIM easier to understand and navigate but also facilitates its extension and adaptation for diverse application needs.

The CIM applications involve using descriptive languages such as the eXtensible Markup Language (XML) or the Resource Description Framework (RDF), both realized within Service Oriented Architecture (SOA) with corresponding platform support by the middleware.

E. APPLICATIONS OF CIM MODELS IN POWER SYSTEMS

CIM models find extensive application across a diverse range of activities within power system operations and planning. Key areas of application include:

- **Energy Management Systems (EMS):** CIM serves as the data model for EMS, which are critical for the real-time operation, monitoring, and control of high-voltage transmission networks [9]
- **Distribution Management Systems (DMS):** Extending beyond transmission, CIM is increasingly utilized in DMS for the management, analysis, and optimization of power distribution networks, especially with the growth of distributed generation [10].
- **Power System Planning:** CIM can play a vital role in various planning activities, including long-term network expansion studies, short-term operational planning involving load flow and contingency analysis, and the integration of new resources like renewable energy. The network planning is going to be covered by the IEC 61968-7 standard which is under development.
- **Market Operations:** In deregulated electricity markets, CIM is enabling data exchange between different market participants, including utilities, independent power producers, and market operators, supporting functions like energy scheduling and trading. The IEC 62325 series of standards further extends CIM for energy market communications [11].
- **Common Grid Model Exchange Specification (CGMES):** A specific application of CIM is CGMES, developed by the European Network of Transmission System Operators for Electricity (ENTSO-E) [12]. CGMES defines a standardized format based on CIM for the exchange of grid models between transmission system operators for various purposes, including system planning and operational studies. The Common Grid Model Exchange Specification (CGMES) is an IEC technical specification (TS) based on the IEC Common Information Model (CIM) family of standards, which was developed to meet necessary requirements for TSO data exchanges in the areas of system development and system operation. The CGMES can be applied by applications dealing with power system data management, as well as applications the most common analyses (power flow, contingency analysis, short-circuit calculations, capacity allocation, dynamic security assessment) [12].
- **Asset Management, Outage Management, and Work Management Systems:** The IEC 61968 series of standards extends the CIM to cover aspects related to the management of utility assets, the handling of planned and unplanned outages, and the coordination of work activities, enabling better integration between these systems and the core operational systems [6].

These diverse applications underscore the central role of CIM in facilitating data integration and interoperability across the power industry.

III. INTERRELATION BETWEEN REAL-TIME COMMUNICATIONS AND CIM MODEL

Together with the CIM model, it is also recommended to use a standarized communication protocol to collect the information from the station. The best option is the IEC 61850 another IEC backed standard, which widely use in AC distribution and transmission substations, and it also includes a data structure which can be mapped to the CIM models [13], this will ensure a real time synchronization between the field measurements and signals and the digital twin.

While CIM represents a significant step towards achieving interoperability, the power industry also has the challenge of ensuring harmonization between CIM and other relevant standards, most notably IEC 61850, which defines the Substation Configuration Language (SCL) used for substation automation. Although both standards aim to standardize data exchange, they were developed independently and have certain differences in their structure and focus. Ongoing efforts, such as IEC 62361-102 CIM - IEC 61850 harmonization [13]–[15], are dedicated to mapping and integrating these models to ensure a more cohesive and consistent flow of information across different layers of the power system, from the control center down to the substation level. The coordinated work of both standards is crucial, as IEC 61850 is becoming the most standard method for real time data exchange inside electrical sites, while IEC 61970 is key to transfer site information between systems, so a standarized mapping between both will facilitate vastly their smooth work.

Another important point to choose IEC 61850 as the communication protocol for real time data transfer is the substation equipment usually has IEC 61850 available while CIM models are restricted to control center applications, so the data collection from the physical twin to the virtual twin will be straight forward.

IV. TECHNICAL SUITABILITY FOR HVDC APPLICATIONS

CIM has achieved widespread adoption in transmission system operations globally, supported by major utilities, system operators, and technology vendors. This existing ecosystem provides several advantages for HVDC digital twin implementations:

- Proven Interoperability: CIM-based systems have demonstrated successful multi-vendor interoperability

	IEC 61970 CIM	IEC 61850
Data structure	Yes	Yes
Communication protocol	Yes	Yes
Focus	Systems inside and outside the station share multiple types of information and data.	**Real time** data inside the station
HVDC elements	Yes	Yes
Complex implementation	Yes	Yes

FIGURE 5. IEC 61850 - IEC 61970 comparison

in numerous grid operations environments, providing confidence in its technical viability for HVDC applications.

- Available Tools and Expertise: The maturity of CIM has generated substantial tool support, including model validation utilities, data translators, and software libraries. Professional expertise in CIM implementation is widely available, reducing implementation risks.
- Integration with Grid Operations: Many transmission operators already utilize CIM for energy management systems. Adopting CIM for HVDC digital twins enables seamless integration with broader grid modeling and operation platforms, supporting holistic system-wide digital twin environments.
- Semantic Richness: CIM's object-oriented approach provides detailed models for HVDC components including converters, DC lines, filters, reactive compensation equipment, and control systems. The standard defines not only the static characteristics of equipment but also dynamic data required for operational digital twins, including measurements, controls, and status information.
- Established Information Exchange Mechanisms: IEC 61970 includes standardized profiles and exchange formats, particularly through IEC 61970-301 (CIM RDF Schema) and IEC 61968-100 (Implementation Profiles). These mechanisms support both bulk data exchange for model synchronization and incremental updates for real-time operations, addressing the diverse data exchange requirements of digital twins.
- Extensibility: The CIM framework allows for extensions to accommodate evolving HVDC technologies without breaking existing implementations. As HVDC systems incorporate new converter topologies, control strategies, or protection schemes, the model can be extended while maintaining backward compatibility.

A. ARCHITECTURAL FRAMEWORK

A CIM-based data exchange architecture for HVDC digital twins should incorporate several key elements:

- Model Repository: A centralized or distributed repository maintaining the authoritative CIM-compliant model of HVDC equipment and topology, synchronized with the physical plant configuration.
- Data Mediation Layer: Translation services converting between native equipment protocols and CIM formats, handling timing considerations and data quality assurance.
- Real-Time Data Services: Mechanisms for publishing operational measurements, status information, and events using CIM-defined data types and temporal semantics appropriate for digital twin applications.
- Change Management Processes: Procedures ensuring that modifications to physical plant configurations are reflected in the CIM model with appropriate versioning and change tracking.
- Addressing HVDC-Specific Requirements

These improvements facilitate more reliable, accurate system models and scalable application development across the power grid [8]

CIM acts as a common language, enabling systems with inherently different data models to communicate effectively by exchanging information in a standardized CIM format.

V. CONCLUSION

In summary, the Common Information Model (CIM) is a standard focused on interoperability and efficient data exchange within the domain of modern power systems, while the IEC 61970 series of standards provides the essential framework for defining and implementing CIM across different applications and domains within the power industry, including the HVDC stations and systems. While IEC 61850 is the standard for real time communication inside the sites, for distribution and transmissions stations.

So the most reasonable option when looking for which must be the standard to follow for digital twin applications for DC plants is choosing the data structure defined by IEC 61970, easing the exchange of models and information between the systems which compose the HVDC ecosystem applications, while IEC 61850 is the direct solution to obtain real time information, measurements and signals, directly from the site devices.

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