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Data Integration, Co-Simulation, and ADMS Application Development using the Common Information Model

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SUMMARY

Application interoperability and data integration have long been recognized as one of the largest information technology and operations technology challenges within the electric utility industry. Increasing penetrations of large-scale renewables, distributed energy resources, electric vehicles, advanced metering infrastructure, and emerging grid edge devices are now further straining data integration workflows. At the same time, a new generation of energy management systems and advanced distribution managements systems designed with data-rich environments will be needed to ensure reliability of both the bulk transmission grid and distribution systems. The Common Information Model (CIM) can serve as a key enabler of power system model exchange, data integration from multiple sources, and creation of data-rich application environments by providing an ontology and data exchange mechanism that is supported by an increasingly large community of vendors and utilities. The CIM is introduced in the context of creating standards-based platforms to reduce the time, cost, and difficulty of integrating advanced grid functionalities to create a more reliable and resilient grid. Key concepts related to adoption of the CIM, including selection of a CIM profile, creation of a data profile, and selection of a database schema, are outlined. Creation of CIM-based data integration platforms built around a single network model and enterprise service bus is proposed as a notable use case of the CIM, with detailed discussion of the conceptual architecture and data exchange mechanisms used. The GridAPPS-D™ Platform is highlighted as a reference implementation of such a standards-based data integration tool. Real-time co-simulation and application development techniques using native CIM power system models are also discussed.

KEYWORDS

Active Distribution Networks; Common Information Model; Data Integration; Power System Simulation; Smart Grids

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INTRODUCTION

To ensure resilient, reliable, robust, safe, and economic operation of the future decarbonized electric grid, a new generation of energy management systems (EMS) and advanced distribution management systems (ADMS) will be needed. These new software systems and associated power applications will need to operate in a data-rich environment integrating existing supervisory control and data acquisition (SCADA) data and numerous grid-edge data streams. Currently, numerous data sources are available and unable to be aggregated in real time (such as advanced metering infrastructure (AMI) smart meter readings). In the near future, this aggregation problem will be compounded by an array of emerging data feeds from internet-of-things (IoT) devices, smart inverters, and distribution-side micro-phasor measurement units (PMUs). Assembling, aggregating, and correlating these disparate data sources will be essential to ensuring that future applications and power system operators have sufficient information for real-time situational awareness, decision-making, and optimal control. However, integration and aggregation of these disparate data sources into a data-rich environment has long been recognized as a difficult task with many challenges [1], [2].

Within an electric utility planning and operations context, there are two aspects to data integration. The first aspect is assembling and aggregating data from disparate sources into a common point of access, often accomplished by feeding all data streams into a data historian. The second aspect relates to correlating data (such as different measurements from adjacent poletop devices) by creating proper relationships between devices, measurements, and control settings. One of the largest challenges of integrating data from disparate sources is that the same vocabulary must be used consistently to describe a particular type of object. This shared vocabulary is then recognized by all applications and users working within the new data-rich environment. Use of an agreed-upon, canonical, semantic information model, such as the Common Information Model (CIM), provides the consensus-based vocabulary and relationships needed such that any CIM-compliant application, service, or software platform can interpret the exchanged data without any custom adapters or data translation.

This paper first introduces the challenges of data integration and application interoperability, as well as why a consensus-based information model and agreed-upon vocabulary are needed. It next presents a use case for using the CIM to reduce the complexity of data exchange and application integration. Finally, the GridAPPS-D reference implementation is introduced. This reference architecture is designed to support data integration, real-time co-simulation, and ADMS application development in a CIM-based platform.

DATA EXCHANGE AND APPLICATION INTEROPERABILITY

In a typical electric utility, there are numerous software solutions that are used and operated independently by the various groups, departments, and organizations within the utility for planning, operations, metering, asset management, model management, and market activities. Each of the software suites used in each department typically uses a proprietary data format, and any data exchange requires manual export and conversion between the formats used by each vendor system. Three strategies (shown in Figure 1a) exist for dealing with the extreme level of effort needed to manage, update, export, convert, and import data formats between different applications and databases.

The first is to reduce the number of databases by purchasing a large software suite from a single vendor. All applications use a single proprietary data format that is internally-integrated and compatible with all the applications needed by utility. This approach is quite effective within a single organization (especially large vertically- integrated utilities), even across the transmission-distribution boundary. It typically requires little information technology (IT) management or data integration effort on the part of the utility because all application use the vendor’s application programming interface (API) and the vendor often performs all maintenance of the databases and interfaces.

However, if software from another vendor is introduced, the structure shifts into the second data exchange approach (Figure 1b), which uses custom application adapters between each set of software.

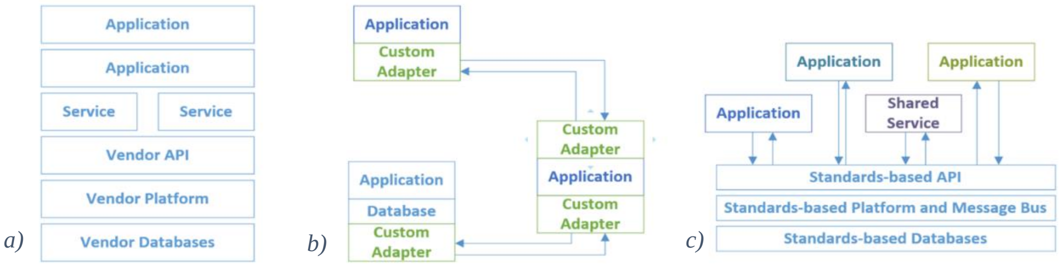

Figure 1: Conceptual representation of a) a vertically-integrated proprietary vendor environment, b) custom adapters between applications from different vendors, and c) a standards-based platform with a unified API and shared services

Each adapter is responsible for converting the data types, message structures, and API calls of one application into a format understandable to the other application. Building custom software adapters is extremely time-consuming and requires a deep understanding of all the data models used by both software suites. It is also very expensive to maintain as any changes to either application or database can break the custom adapter.

The third strategy is to adopt a common data integration platform that allows external integration between multiple software packages using a shared data format, unified API, set of databases, and reusable services (Figure 1c). In this approach, interfaces do not need to be created between each individual application and every other application. Instead, each application only needs a single interface with the standards-based platform, thereby significantly reducing the number of directions in which data needs to be exchanged.

Although the first two approaches are reasonable within a single utility, the complexity of building custom adapters increases nonlinearly with the number of applications that need to exchange information. Consider when data needs to be exchanged between different departments, between control centers, or across the transmission-distribution boundary, the difficulty and overhead of building custom adapters increases nonlinearly with the number of applications to be integrated. As a result, there have been multiple efforts over the years to create interoperability through standards-based protocols and information modeling, starting with the creation of inter-control center communication protocol (ICCP) [3]. ICCP was developed in an effort led by the Electric Power Research Institute (EPRI) to exchange real-time SCADA data among multiple transmission and distribution control centers running EMS and distribution management systems (DMS) from multiple vendors. The ability to exchange real-time data using ICCP was first demonstrated in 1995 with a systematic interoperability test between EMS software platforms from four different vendors [14]. Other efforts to increase interoperability and data exchange include the development of MultiSpeak, OpenFMB, and IEC 61850.

One of the largest issues in creating interoperability between different advanced power applications is the lack of standardization of naming of equipment and their attributes. If multiple applications are to be integrated without development of numerous custom adapters and model converters, it is necessary for all shared services and databases to use a consistent set of object names, identifiers, properties, and relationships for various types of power system equipment. Without such an information model, it is extremely difficult to aggregate and correlate data; it would also require significant amounts of effort to manually format, validate, and correlate asset data, measurements, and network model information.

THE COMMON INFORMATION MODEL AND PROFILES

The Common Information Model (CIM) is an information model that provides a formal representation of objects, their attributes, the relationships between them, and the operations that can be performed on them. One of the most confusing aspects of the CIM to power systems engineers and power application developers is that CIM is not a database structure, physical data store, or even the power system network model. Rather, the CIM is an abstract information model that only provides a consensus-based vocabulary and set of attributes for describing power system networks, assets, and data exchanges. Development of such a consensus-based vocabulary requires a large user community to come together and develop a set of "living" documents that define the terminology and attributes of various things that are important to the community's focus area. The user community responsible for development, expansion and maintenance of the CIM is the UCAiug (informally known as the CIM User's Group).

The CIM Users Group collaborates with the International Electrotechnical Commission (IEC) and other standards communities for the development of technical and informative specifications. The current, past, and draft versions of the CIM information model are available freely through the UCAiug website [4] as set of Enterprise Architect .eap files and CIMTool .xmi files under an Apache 2.0 license. It is important to note that the CIM information model is separate from the IEC standards, although they cross-reference each other. Users can modify the CIM profile, add custom attributes, or create entirely new extensions (such as representation of house appliances). For example, the GE eTerra EMS/DMS Model Export tool uses a custom CIMDNOM profile derived from the base CIM 15 information model [5]. Likewise, the PNNL GridAPPS-D platform uses a set of custom extensions for residential houses and IEEE 1547-compliant DERs derived from the base CIM 17 information model [6].

As a canonical information model, the CIM is a superset of multiple information models for describing electrical network models (corresponding to IEC 61970), asset management information (corresponding to IEC 61968), and transactive market activities (corresponding to IEC 62325). It contains a far larger set of classes and attributes than could possibly be needed by a single application or project. It is anticipated that any adopters of the CIM will select only a small subset of classes covering the relevant aspects of the power system model. This subset is known as a *CIM Profile*.

Selection of a CIM profile is based upon a careful needs analysis to determine the minimum set of information needed for the particular data integration objective, as show in the workflow diagram of Figure 2. The functional requirements, data interfaces, usability considerations, and anticipated role of the new application in current business / operations processes should be captured in detail and used as the basis for a concept of operations (ConOps) document. For example, if the objective of a project is to aggregate distributed energy resources (DERs) to the substation feeder breaker, it is likely that only a basic topology model will be needed. Detailed modeling of line geometry, transformer impedances, tap settings, and reactive control modes is not necessary, as none of these attributes impact the connectivity of a DER to its associated energizing substation and feeder breaker. Thus, an extremely small CIM profile could be used to accomplish the DER mapping task. Only a handful of classes (such as ACLineSegment, LoadBreakSwitch, SynchronousMachine, ConnectivityNode, ACDCTerminal, and PowerElectronicsConnection) would need to be included in the selected CIM profile. It is possible either to derive a new custom CIM profile with the minimum set of classes needed or adopt an existing CIM profile, such as those used by EMS vendor exports [5] or open-source tools including CIMHub [7]. It is worth noting that some utilities, such as ERCOT, use multiple CIM profiles for power system model export, with a complete set of attributes stored in the network model manager and dynamic model export depending on whether the model is needed for planning studies, transient stability analysis, or market participation.

The selected CIM profile is used to create a *data profile* to contain the power system network model. It is important to note that the data profile is not the power system data. A data profile is an empty file structure that specifies how the network model data should be organized in a file. The selection of a particular data profile schema is not related to adoption of the CIM, but rather the personal preferences of the software development team. Data profiles created using eXtensible Schema Definition (XSD) are very popular because they can be used to validate the eXtensible Markup Language (XML) files commonly used for power system model files. Javascript object notation (JSON) schema is another common choice because they are identical in structure to Python dictionary objects and easily parsed by simple Python scripts.

Finally, the data profile can be populated with the power system network model data, usually through a custom script that script that interprets the empty data profile and uses the specified structure to build

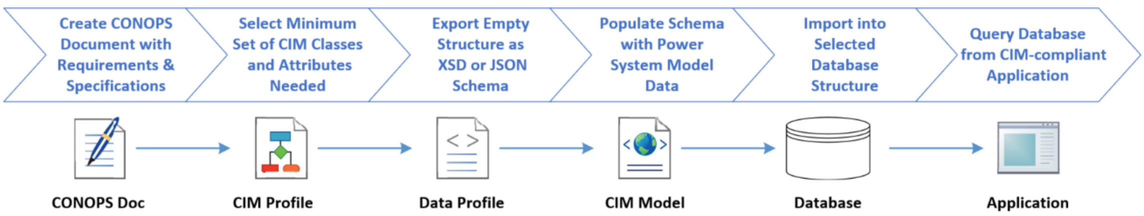

Figure 2: Workflow for adopting the CIM from requirements analysis to application implementation

a file that contains the actual power system network model data. XML files are the most popular format for CIM power system model data due to the ease of interpretability with web-based tools and the ability to validate the network model file for any syntactic or semantic errors. The network model can then be ingested into a database for use by advanced applications and shared services. Common choices include relational, triple-store, and graph databases, which each have their own advantages and disadvantages that are discussed in more detail in [6], [8].

One of the critical steps in the model conversion process is establishing a persistent set of Universally Unique Identifiers (UUIDs) to be used as the Master Resource Identifiers (mRIDs) for all network parameters, asset characteristics, and available SCADA measurements. In CIM-based applications, the mRID is used as the unique pointer or dictionary key that allows all the properties of a particular piece of equipment to be called from memory or queried from a database. Measurement mRIDs are also defined for all SCADA, AMI, and other measurements that are to be aggregated and made available to advanced applications. The mRID does not have to be human-readable and is generally not intended to be displayed to end-users of advanced power applications. This 3-18 character identifier is intended to be used by software systems for consistent identification of network data and asset information. Global uniqueness of mRIDs can be easily achieved by using a Universally Unique Identifier (UUID), also known as a Globally Unique Identifier (GUID), for the mRID of every object and measurement in the power system network model. For user interface support, the CIM includes the attributes name, description, aliasName, and pathName for providing identifiers that are human-readable. Although this approach of defining mRIDs for every object and every measurement may seem unnecessarily complex at first, it greatly simplifies the format not only for querying for power system network model information, but also for publishing and storing measurements in real-time.

CIM-BASED DATA INTEGRATION PLATFORM ARCHITECTURE

There exist numerous utility use cases for use of the CIM, ranging from simple model export/import for data transfer between different vendor software to complete organization-wide data integration across all planning, operations, and business activities using a single CIM power system model and enterprise message bus (ESB). A handful of these use cases are discussed in detail in [8]. One such use case will be given special attention, namely the development of standards-based platforms around the CIM for creating data-rich environments to host the next generation of EMS and ADMS applications.

Figure 3 depicts a conceptual representation of a data integration platform based on the CIM to combine disparate data sources in real time and make them available to shared services and advanced applications. Such a CIM-based platform enables multiple applications to work within a single data-rich environment, working from a single set of databases that all use the CIM to represent the power system model with consistent use of the same classes, attributes, and master resource identifiers (mRIDs). All applications compliant with the CIM standard will be able to interpret any network model in the platform with no code customization and will also be able to use consistent mRIDs to reference equipment across multiple databases, data streams, and even "study-mode" simulations run with offline simulators.

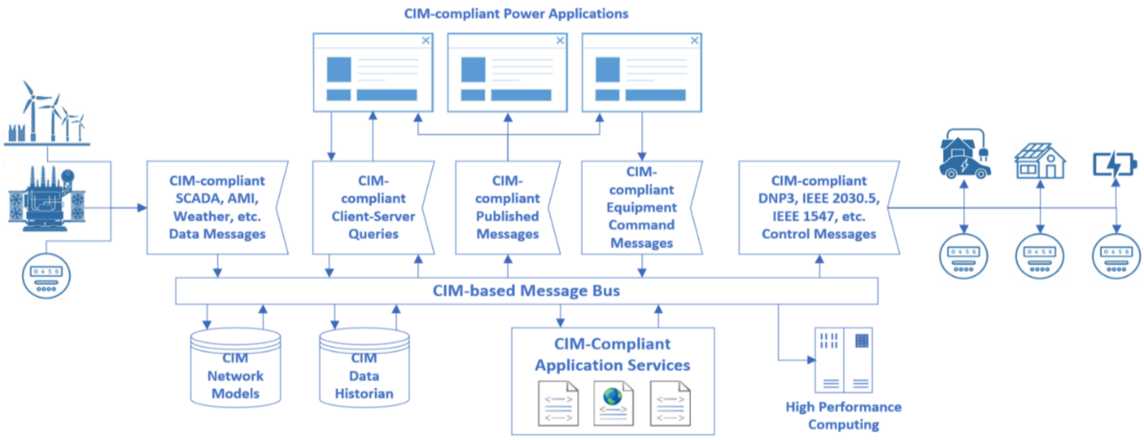

Figure 3: Conceptual representation of a CIM-based platform for creating a data-rich EMS / ADMS environment.

Interaction of the applications and services with the platforms follows a set of standardized message formats and messaging use cases defined in IEC 61968-100:2022 [9]. Two CIM-compliant messaging paradigms based on interaction through an enterprise service bus (ESB) should be noted in particular. The first is *request/reply using an ESB*, in which an application or service creates a CIM-compliant request message and sends that message to the message bus. The message bus then delivers that message to the particular database or service to which the message is intended. The recipient generates a CIM-compliant reply message, which is passed through the message bus back to process that made the original request. The second messaging use case is *publish/subscribe using an ESB*, in which CIM-compliant messages are published on the message bus and are available to all applications and services that are interested in receiving that type of message. This paradigm is extremely useful for aggregating real-time data streams and making them available in real time so that applications can subscribe to a single message bus. This context can also be used for publishing customer incentive signals, smart inverter control settings, or other control commands to a large number of subscribing equipment assets.

In the conceptual CIM-based data integration platform presented in Figure 2, data from multiple disparate sources (such as SCADA measurements, weather info, and smart meter data) are aggregated and published to a CIM-based message bus. These data streams are mapped to the terminals of associated power system equipment through a set of unique measurement mRIDs defined for each measurement ingested by the platform. The ingested measurements, power system network model, and associations are contained in a set of databases structured around the unique mRIDs and directional relationships between the set of CIM classes and attributes used.

CIM-compliant advanced power applications can then pass request/reply queries through the message bus to the CIM-based data stores and shared services to obtain network model information, historical data, snapshot power flow results, and other static data. Applications can also subscribe to streaming data, which are published in real time as CIM-compliant messages on the message bus. Shared services and applications within the platform can publish real-time information (such as the current network topology or latest Y-bus matrix) or publish CIM-compliant equipment control commands through the message bus. These messages can then be converted to the format of any specific communications protocol (such as DNP3, IEC61850, IEEE 1547, etc.) and sent to physical equipment controllers.

The architecture of the CIM-based data integration platform discussed also reduces the number of interfaces and code duplication between applications and services. A single application service, such as topology processor, can run in real-time and publish the current topology of the power system to the message bus. Then, all power applications that require the current topology can simply subscribe to the service output through the CIM-based message bus, rather than run their own internal topology processing script. Because all equipment control commands are published through the shared message bus, any application can subscribe and recognize if a different application is already issuing control commands to a particular asset through its unique mRID, laying a foundation for development of platform-based and application-based coordination and deconfliction.

GRIDAPPS-D PLATFORM AND REFERENCE IMPLEMENTATION

An example of such a CIM-based platform and data-rich environment is the application development ecosystem and reference architecture implementation developed by the GridAPPS-D program [6], [10], [11]. As part of the project, sponsored by the US DOE Office of Electricity Advanced Grid Research Program, a series of extensions for CIM-based modeling of North American distribution equipment have been introduced, as well as the development of a standards-based data integration and co-simulation software ecosystem, known as the GridAPPS-D™ Platform.

The GridAPPS-D Platform was developed as the first reference implementation of an open-source data-rich platform for distribution system data integration based on CIM representation of data models, programming interfaces, and data exchange interfaces. The GridAPPS-D platform provides industry, researchers, and utilities a well-documented roadmap to developing CIM-compliant applications, services, and data integration bridges to demonstrate new grid functionalities and use cases. CIM-compliant messaging is utilized between all grid devices in the field, distributed applications in utility systems, and centralized applications that are integrated within the platform environment. Through use of the CIM and other industry standards (such as DNP3, IEEE 2030.5, and OpenFMB), it is intended

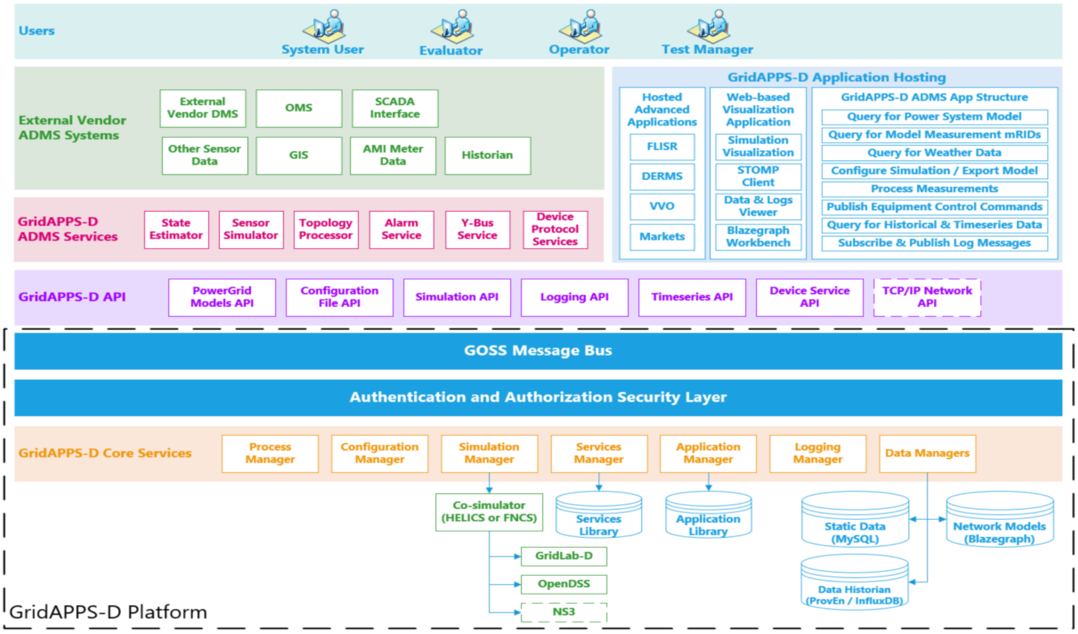

Figure 4: Architecture of GridAPPS-D Platform, which serves as a reference implementation of the conceptual CIM-based data integration platform illustrated in Figure 3.

that the application development environment is independent of any specific proprietary data formats and capable of interacting with existing vendor ADMS environments. It should be noted that the GridAPPS-D platform is not intended to serve as a replacement for industry ADMS tools or as a production-grade control room software suite, but rather as a flexible, open-source sandbox for co-simulation and development of new tools and concepts that are not feasible without a data-rich environment and standards-based interfaces between portable applications and reusable services.

A key concept within the GridAPPS-D Platform architecture (illustrated in Figure 4) is the separation of data integration workflows from development of new application functionalities. All data integration and model representation are performed within the containerized software environment illustrated inside the dashed line. All power system network models are represented natively using a CIM profile based on the latest CIM 17 and CIM 18 drafts with an additional set of extensions for modeling behind-the-meter house appliances and loads. The model data is ingested using the CIMHub tool [7], which uploads the CIM XML model into a triple-store database, generates measurement mRIDs for all available SCADA / grid edge metering points, creates residential house load objects, and runs power flow validation studies using the open-source OpenDSS and GridLAB-D solvers. The CIM power system model is used as the single reference point for all applications and services, which obtain modeling data dynamically through request/reply messages passed through the standards-based message bus via the PowerGrid Models API. As a result, compliant applications and services are able to scale seamlessly across different network models without modifications to the modeling code.

Exchange of messages and real-time data is performed through a set of JSON text strings that are passed through the message bus using the request/response and publish/subscribe paradigms discussed earlier. Queries for power system model data, equipment/measurement mRIDs, weather data, historical data, and converted .dss or .glm executable files are made on a request/response basis. Incoming SCADA measurements, grid-edge data, and real-time co-simulation results are published every three seconds onto the message bus (Figure 4). Compliant applications and services can subscribe to incoming messages and subsequently publish real-time equipment control commands or reusable service output messages (such as real-time topology or admittance matrices). Equipment control commands, formatted as CIM Difference Messages, are then converted to specific device protocol messages using common standards (such as DNP3, IEEE 2030.5, or OpenFMB) and delivered to physical equipment objects that are subscribed to the message bus or connected through one of the device protocol bridges. For full CIM compliance, the simple object access protocol (SOAP) structure specified by the IEC standards is also supported by the GridAPPS-D Platform. All data passed through the message bus is archived in the Timeseries Database, which functions as a CIM-compliant data historian.

CO-SIMULATION AND APPLICATION DEVELOPMENT ENVIRONMENT

In addition to providing a standards-based data integration solution, the GridAPPS-D platform offers a co-simulation and application development environment for demonstrating new grid functionalities for both small utilities [10] and academic research [11]. The GridAPPS-D platform offers a set of co-simulation capabilities comparable to those of a dispatcher training simulator (DTS) through integration with open-source power flow and thermal end-use simulators, including OpenDSS and GridLAB-D. Co-simulation capabilities are facilitated through CIM-based software bridges between the message bus and the Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS), which is a high-performance transmission-distribution-communication-markets co-simulation framework [12], [13]. Data streams provided by the GridAPPS-D platform through the co-simulation bridge include real-time measurements, smart meter data, controllable customer appliances, rooftop solar, dispatchable DERs, and traditional voltage-control equipment. Co-simulation configuration is handled through the web-based graphic user interface or a JSON simulation request message created using the Configuration File API. The visualization application provides a one-line diagram of the feeder, colorized switch positions, outage locations, and alarm messages. During a simulation, power flows, node voltages, and tap positions can be plotted through customizable strip charts. Equipment setpoints (such as switch positions, DER setpoints, shunt capacitors, and regulator taps) can be controlled through the user interface or by passing CIM difference messages through the message bus.

Scripted scenarios (including faults, communication outages, and equipment malfunctions) can be configured using the Test Manager feature. Multi-user role-based simulation is also possible with dedicated operator, evaluator, and test manager roles. Applications can also be benchmarked against the combination of IEEE Test Feeders, PNNL Taxonomy feeders, and other realistic synthetic models included by default in the GridAPPS-D Platform. Realistic evaluation can also be performed in mock control room environments using blue/grey/black-sky operational scenarios corresponding to common control room tasks, such as hot-work clearances and outage response. Finally, additional models and actual utility feeder data can be uploaded easily as CIM XML files using CIMHub [7] for application testing and real-time simulation.

Applications can run in a centralized, hierarchical, or distributed context using real-time simulations or testbed data streams ingested via DNP3 or other standard communication protocols. CIM-compliant applications developed using GridAPPS-D or other standards-based platforms have native portability and reusability with other CIM-compliant applications and services to provide ADMS functionalities including FLISR [14], volt-var optimization [15], distributed state estimation [16], distributed energy coordination [17], and optimal dispatch of DERs [18]. Any GridAPPS-D code may be incorporated into a commercial product, pursuant to its open-source Berkely Software Distribution (BSD) license terms. Detailed documentation of the Python API and platform architecture is available on ReadTheDocs [19] and as a set of interactive iPython notebooks hosted on the project GitHub [20], which also contains the source code for the Platform and all shared services. The GridAPPS-D platform can be installed on a cloud server or local Linux virtual machine by cloning the repository and running the installation script.

CONCLUSION

This paper introduced some of the challenges of creating data-rich applications environments needed to ensure reliable operation of the future decarbonized electric grid. Many of the associated challenges can be overcome by adoption of standards, such as CIM, which is an agreed-upon information model developed by a set of committees within the UCAiug to provide a consensus-based vocabulary for describing power system networks, asset information, operational procedures, and market data in a consistent manner. The structure of the CIM enables creation of standards-based data integration platforms based on an enterprise message bus and unified power system network model that is used by all compliant applications and services. Application interoperability is simplified due to elimination of application-to-application adapters and reduction of the total number of interfaces because each application communicates directly with the enterprise message bus. The GridAPPS-D Platform is introduced as a reference implementation of a standards-based data integration architecture. It also supports co-simulation and application development by providing numerous synthetic power system models, multiple shared ADMS services, and a Python API for demonstrating and evaluating application functionalities. As increasingly more electric utilities adopt the CIM, it is anticipated that standards-based data-rich environments will emerge as a preferred solution to data integration challenges associated with increasing penetrations of renewables, DERs, and grid-edge devices.

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