Utilizing Standards-based Semantic Services for Modeling Novel Smart Grid Supervision and Remote Control Frameworks

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Abstract—Smart Grids accelerated evolution has introduced numerous approaches for solving issues such as increased electricity demand, large scale integration of distributed energy resources and power market deregulation. All these approaches have a common aim of coexisting in multi-vendor environment of the Smart Grid. To provide a solution for integrating diverse stakeholders in the Smart Grid, it is required to utilize well accepted industrial automation standards which will enable seamless integration of new systems and maintain backward compatibility with legacy systems. As a result of analysis, IEC 61850 and IEC 61970 have been recognized as fundamental industrial standards for successful Smart Grid deployment.

This article shows how combined usage of IEC 61850 and IEC 61970 provides prerequisites for modeling unified Smart Grid ontology and constitutes deployment groundwork for standards-based semantic services. By using service-oriented and event-driven architecture design principles, a novel approach for modeling Smart Grid supervision and remote control frameworks has been presented.

I. INTRODUCTION

Although there is no standard global definition, Smart Grids are usually defined as electricity networks that can intelligently integrate behavior and actions of generators and consumers in order to efficiently deliver sustainable, economic and secure electricity supplies [1]. Research institutions [1, 2], standardization bodies [3, 4] and global industrial leaders [5] have brought up several interoperability roadmaps which define requirements for future Smart Grids. All mentioned guidelines basically agree on the same principle – the standards-based integration of intelligent solutions is the key prerequisite for a feasible Smart Grid deployment. Also, all mentioned guidelines recognize IEC 61850 [6] and IEC 61970 [7] as the two most important standards which provide groundwork for seamless integration of devices and applications intended for power system automation. These standards define semantics for power system related data and also standardize data-exchange service interfaces required for supervision, protection and control in the Smart Grid.

Standards-based services significantly facilitate integration of new solutions into the current power system and they by no means restrict Smart Grid functionalities. Semantic services presented in this article allow modeling novel Smart Grid supervision and remote control frameworks with help of state-of-the-art software integration techniques.

Paradigm shift from centralized and self-contained power systems towards decentralized and envisioned Smart Grid requires backward compatibility with legacy systems. Both IEC 61850 and IEC 61970 include capability of integrating diverse legacy devices and applications. IEC 61850 includes remapping mechanisms for commonly used remote control protocols [8], while IEC 61970 provides component-based integration approach for currently used applications in power utilities [9]. Hence, combined usage of these industrial specifications provides a favorable groundwork for realizing gradual transition towards the Smart Grid.

The following chapter shows relationships between IEC 61850 and IEC 61970 semantic models and outlines requirements for their harmonization and creation of unified Smart Grid ontology. The third chapter analyzes prerequisites for designing standards-based semantic services which are basic elements of Smart Grid integration frameworks. It is also presented how these novel frameworks are related to a number of state-of-the-art design principles and integration techniques required for implementing different supervision and remote control functionalities used in Smart Grid utilities. As an example of applying Smart Grid ontology, virtual power plant (VPP) [10] semantic modeling principles are presented in the fourth chapter. VPP is a controllable portfolio of distributed energy resources (DERs) and it is used as a generic use case of Smart Grid information model which provides semantic layer for heterogeneous devices. In the end, an exemplary Smart Grid framework is presented. This framework is based on service-oriented and event-driven architecture design principles. This approach is motivated by implied characteristics of IEC 61850 enabled Intelligent Electronic Devices (IEDs) as SOA-ready [11] devices. The developed framework demonstrates how it is possible to utilize original IEC 61850 data exchange services as basic semantic integration components which provide foundation for adaptable Smart Grid deployment environment in standards-compliant electric utilities.

II. UNIFIED POWER SYSTEM ONTOLOGY

Significantly large number of participants in the complex and evolving Smart Grid requires existence of unified power system ontology. This condition is essential for seamless integration of new devices and applications into power system and mandatory for realizing backward compatibility with legacy systems during transition period from traditional power
systems. To a great extent, power system semantics can be obtained by utilizing IEC 61850 and IEC 61970 information modeling capabilities. Despite the fact that both standards represent the same domain knowledge, there are some crucial differences which complicate creating unified ontology. The future-proof Smart Grid frameworks require existence of unified power system ontology.

A. IEC 61850 device model

Data semantics provided by IEC 61850 are based on describing device functionalities in utility subsystems such as substations [12], wind power plants [13], hydro power plants [14] and DERs [15]. IEC 61850 information models [16] are based on object-oriented modeling of process data required for the power system automation. Figure 1 shows relationships between IEC 61850 classes and instance examples.

Top parent class is the Server which represents a physical device, i.e., a device controller. The server can consist of one or more logical devices (LDs), i.e., virtual representations of devices intended for supervision, protection or control. LDs are created by combining several logical nodes (LNs) which represent various device functionalities and are crucial part of IEC 61850 data semantics. First letter in LN notation designates function name (e.g. DPVM – photo voltaic module, WROT – WPP rotor, MMXU – measurement unit). Data objects (DOs) are groups of data attributes (DAs) which are IEC 61850 endpoints and are granular LN elements. Both DOs and DAs can be recursively nested. A typical IEC 61850 DO contains at least three DAs: val (the data value), q (the data quality) and t (the data timestamp).

IEC 61850 offers elaborate device data model with twofold perspective, i.e., runtime exchange data and device configuration data. Runtime data can be obtained through self-descriptive semantic services provided directly from devices [16], while configuration data are contained in XML documents based on Substation Configuration description Language (SCL) [17].

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B. IEC 61970 power system model

International standard IEC 61970 defines application programming interfaces (APIs) for Energy Management Systems (EMS) commonly used in utility control centers [9].

Most important document in IEC 61970 series is IEC 61970-301 [7] which defines Common Information Model (CIM), i.e., power system semantics required by various power utility applications. CIM is based on using Unified Modeling Language (UML) [18] to describe real world objects and information entities used for utility’s operational systems such as EMS or Supervisory Control and Data Acquisition (SCADA) systems. CIM specifies semantics and structure for data which represent power system resources (e.g. a substation, a transformer, a switch), their attributes (e.g. value of the active power) and their relationships (e.g. transformer has a two windings). CIM data classes, attributes and their relationships are divided into several packages which define logical views on functional aspects of specific utility operation. Applications using CIM usually combine several packages. Figure 2 shows an excerpt of CIM UML model related to SCADA package.

IEC 61970 offers comprehensive data model intended for independently developed applications with soft real-time requirements. First IEC 61970 editions were closely related to transmission system, but requirements for distribution automation lead to development of data model extensions for distribution system [19].

C. Harmonization problem

Despite that IEC 61850 and IEC 61970 both represent power system domain vocabulary, there are some crucial issues which complicate their seamless integration. These issues are results of independent standardization efforts of various IEC’s working groups. This problem has been only partly addressed by introducing reference architecture for IEC Technical Committee 57 (TC57) [20]. Harmonization problem has been identified in [21] and has been a part of several research projects ever since.

IEC 61850 data model is a result of elaborate domain analysis. Despite introducing classes and inheritance, final model is not entirely object-oriented. This is caused by specific device-oriented semantics required by centralized applications used in substation automation. IEC 61850 standard extensions, such as IEC 61850-7-420 [15],...
introduced requirements to use IEC 61850 for decentralized automation systems such as VPPs. One of the models merging approaches is based on development of IEC 61850 UML model [21]. Because of different mandatory attributes, attribute levels and specializations it has been shown that without changing both standards it is impossible to realize bi-directional mapping of data by using aforementioned approach. EPRI’s harmonization efforts [22] have resulted in introduction of required customizations of IEC 61850. Only recently, ontology integration [23] has been presented as applicable approach which can guarantee data integration paradigm without changing both standards. This approach is based on presenting IEC 61850 and IEC 61970 data models with Web Ontology Language (OWL) [24]. OWL is state-of-the-art technology for ontology representation.

Most notable example for utilizing unified power system ontology, provided by any of previous solutions, is possibility to model semantic services which could accelerate Smart Grid adoption and assure its future-proof evolution.

III. SERVICE-ORIENTED SMART GRID

Service orientation is a design paradigm which decomposes a system into its functionalities, where services are the elements composed of process functions which cannot be further decomposed [25]. The services are autonomous, platform-independent entities which can be described, published, discovered and assembled. Service oriented architecture (SOA) is considered as an effective approach for building integrated, heterogeneous and distributed applications by using services as building blocks. SOA represents an emerging platform for industrial automation systems and provides an applicable software design principle for real-time environments [26]. SOAs are inherently synchronous and utilize request/response interaction pattern. To use a service, a client needs to know the service interface and invoke the appropriate operation [25].

Diversity of Smart Grid participants requires existence of various types of power utility services. All high-level services in the future Smart Grid will heavily depend on data services provided from utility subsystems. The crucial requirements for subsystem-level services have been identified as:

- an open and unified information architecture (standards-based data, platform-independent services);
- automatic detection of device capabilities (plug-and-play principle, self-descriptive services);
- runtime scalability of controlled device group (adding or removing controlled devices during operation);
- flexible data management at backend applications (organization of specific data sets);
- quality of data services (ensuring acceptable time delays, reliability and security);
- agility through adaptability and reconfigurability.

According to these requirements, data service interfaces provided by IEC 61850 and IEC 61970 have been analyzed.

A. Abstract Communication Service Interface

The Abstract Communication Service Interface (ACSI) [16] is a new paradigm, introduced by IEC 61850, that describes data exchange procedures. ACSI model classes define standardized data exchange services for IEC 61850 devices. The ASCI model classes required for vertical communication are those enabling:

- creation of application connection with a device (the Application association model);
- browsing and editing device information model (the Server/LD/LN/DO/DS models);
- changing active settings group (the Setting-Group-Control-Block model);
- sending commands (the Control model);
- event notification mechanism (the Report-Control-Block models).

These ACSI model classes [16] can be used as standards-based data services for variety of Smart Grid devices. Thus, any IEC 61850 enabled client software can take full advantage of device remote control, i.e., obtain current device states or measurements, change device operational state or send control commands. ASCIs are independent on application mapping and can be realized using any generic middleware [16]. Hence, any IEC 61850 IED, that enables ACSIs required for vertical communication, can be regarded as SOA-ready device [11] with mature platform-neutral data services.

B. Generic Interface Definition

The GID (Generic Interface Definition) [27] is set of APIs defined in IEC 61970 for exchanging CIM related information between power utility applications. It is based on existing interface standards (Classic OPC [28-30] and OMG industrial systems specifications [31-33]) in order to provide additional functionality required by applications dealing with utility operations. GID can be classified into 4 types:

- Generic Data Access (GDA) defines information exchange interface for generic data (e.g. model changes);
- High-Speed Data Access (HSDA) provides access interface for the real-time data (e.g. measurements and operational state changes);
- Generic Event and Subscriptions (GES) defines interface for sending event data (e.g. events and alarms relevant to specific topic);
- Time-Series Data Access (TSDA) defines access interface for the data measurement history (e.g. data changes during certain time period);

APIs used for realizing GID do not offer semantic data modeling capabilities which would enable seamless integration of new services into the Smart Grid. In this article it is shown how this problem can be solved by using standards-based services and unified power system ontology.
C. Standards-based service mash-ups

Despite that both IEC 61850 and IEC 61970 define standards-based data interfaces, there are several critical issues needed to be solved before their formal integration. One basic difference is that ACSIs are abstract and not coupled to any middleware, while GIDs is strictly defined as the APIs. Another problem is that each of ACXI services defines state-machines for transitions between various device states while these transitions are not realizable via any of GID APIs. Therefore, usage of common data exchange interface is not possible without specific technology enabler. Current standardization efforts regarding IEC 61970 are pushing towards usage of newly defined OPC Unified Architecture (UA) [34] specifications. OPC UA provides semantic data integration into data exchange services and thus acts as a promising candidate technology for successful semantic service deployment in Smart Grid. OPC UA also defines wrapper technology for Classic OPC servers used in currently available IEC 61970 implementations. Furthermore, OPC UA provides data modeling capability and supports ACXI implementation requirements. Besides OPC UA, another possible solution is the usage of embedded implementations of web service stacks defined in Devices Profile for Web Services (DPWS) [35]. Most prominent DPWS candidates are SOA for Devices (SOA4D) [36] and Web Service for Devices (WS4D) [37]. These and similar technologies enable full-blown SOA-ready devices [11] which would significantly reduce integration time frame for variety of devices and applications in next-generation energy networks. Figure 3 outlines semantic service levels and relationships among standards-based Smart Grid devices and applications.

Smart Grid utilities require semantic services that will enable their location transparency, referential integrity and seamless composition. Hence, by using any of aforementioned technologies as an intermediary between IEC 61850 and IEC 61970 models, standards-compliant utilities can benefit from unified ontology provided by devices and applications.

IV. CASE STUDY: DISTRIBUTED CONTROL OF VIRTUAL POWER PLANTS

Effortless integration of distributed energy resources into the power systems is one of the most difficult and daunting tasks for the Smart Grid. One major pitfall of cooperative DER control is using disparate communication platforms and proprietary semantic models. Using IEC 61850-7-420 [15], i.e., IEC 61850 extensions for DERs, utilities can overcome these issues. Unfortunately, semantic models provided by this and similar IEC 61850 extensions only allows DER semantic integration at the level of subsystem (e.g. VPP automation system). Fully compatible integration of DERs requires semantic coupling of DER information with CIM. Thereby, power system applications can have significant benefits from real-time DER-related information at control center level. Another problem is realizing specific set of subsystem-level semantic services required to enable remote control of VPPs.

The following sections demonstrate capabilities of standards-based semantic modeling of VPPs and show how subsystem-level semantic services provide control framework required for abstraction of multiple DERs in VPP model.

A. Standards-based VPP semantics

Figure 4 shows generic VPP semantic modeling principles. The modeling is done according to IEC 61850 modeling rules and definitions [16]. The detailed IEC 61850 model is created for solar power plant. The model is granulated at the level of LN, which are grouped into functional scopes in order to specify the most significant functions defined in IEC 61850.

A detailed description of each of LNs and related DOs is beyond the scope of this paper and can be found in [12, 15]. The LN selection depends on specific control functions which take into account electrical, physical or meteorological measurements, along with device control abilities. Figure 4 shows that the IEC 61850 provides generic and adjustable modeling capabilities required by diverse and variable Smart Grid applications. To reduce integration difficulties and application (re)engineering, each of IEC 61850 LNs should be presented in CIM model. Newly created information model would provide value-added feature for variety of possible Smart Grid applications. IEC TC57 WG13 has made a new work proposal which will result in creating CIM extension for generation [38]. This document will define relationship between IEC 61850 and CIM semantic models used for generation what should be backbone for seamless integration of DERs in to the Smart Grid.

B. Subsystem-level semantic services for VPP control

ACXI services abstract diversity of device functionalities and provide key aspect for large scale DER integration. ACSIs can be used for information retrieval from the DERs therefore enabling management of the current VPP model, sending

Figure 3 Semantic service levels in standards-compliant Smart Grid

Figure 4 VPP data modeling principles with IEC 61850 and CIM
commands to each DER or changing endpoint settings. Gathering DERs into VPP enables deployment of high-level services such as ancillary services which are based upon standards-compliant data exchange services (i.e. ACSI).

Specific subsystem-level semantic services provide service-oriented framework for realizing various VPP objectives. These semantic services have been identified as follow:

**The Driver service:** The service responsible for creating and maintaining application connections to multiple DER servers. This service utilizes the Application association model ACSI from each DER thus providing information about established connections. The number of connections between the client application and multiple servers (DERs) is not limited by IEC 61850 [16].

**The Ontology service:** The VPP control system requires knowledge about functionalities of currently connected DERs. This can be realized by utilizing the information modeling ACSIs from all DERs which are part of VPP. The Ontology service provides information about all currently available VPP functions (LNs) and their endpoint settings (DAs).

**The Management service:** The VPP control depends on the possibility to change endpoint settings of controlled DERs and ability to send control commands. Thus, the Setting-Group-Control-Block (SGCB) model and the Control model can be grouped into a common service, i.e., the Management service. The Ontology service obtains information about the controllable VPP LNs, whereas the Management service through SGCB model can adjust DAs for specific optimization routines or start/stop specific control function via the Control model.

Besides Report-Control-Block (RCB) models, all other ACSIs are based on request/response message exchange pattern and can be directly used as SOA services. RCB ACSI is used for vertical event dissemination and it is inherently asynchronous service.

The event-driven paradigm [39] facilitates events as a means of information exchange by using publish/subscribe interaction pattern which is part of RCB models. This pattern is based on publishing events to the mediator who forwards events to the event subscribers. Therefore, it is required to define specific service which has event producers, event consumers and subscription mechanism. For these reasons the event broker service has been introduced.

**The Event Broker service:** In order to realize IEC 61850 event dissemination it is required to provide broker between event producers (ASCI servers) and event consumers (ACSI clients). This service maintains subscriptions of RCB ACSIs from each server (e.g. DER) and acts as event broker. Subscribed IEC 61850 events are defined in data-sets via DS model ACSI and are handled by this service.

The described services define generic subsystem-level-semantic services which can be used for controlling DERs in the VPP model. These services are based on standardized IEC 61850 ACSIs. Thus, they are not constrained by any proprietary information model, can be realized using variety of middleware mappings and can be easily adapted for any control objective. Figure 5 shows relationships between ACSI services and subsystem-level services.

**C. Composing subsystem-level semantic services**

Specific composition of proposed subsystem-level semantic services provides adjustable framework for novel high-level services which take advantage of ACSIs capabilities. Any high-level service can invoke subsystem-level semantic services in specific order to ensure real-time remote control and supervision of field devices. This procedure is illustrated in Figure 6 and can be described as following:

1. The Driver service creates application connections with DERs.
2. The Ontology service retrieves DER semantic models, creates VPP model and provides it to high-level service.
3. Based on the high-level service function, the event subscriptions (DS models) are created and assigned to the Event Broker service.
4. After starting high-level service, the subscribed events are continually received through the Event Broker service. Based on the high-level service objective, endpoint settings are calculated and sent to DER controllers via the Management service.

This procedure acts as a generic semantic service wrapping methodology in case of controlling IEC 61850 devices.
is not restricted to implementation of VPP automation systems only. The same principles can be used for controlling substations, wind power plants or any other subsystem modeled with IEC 61850 semantic models. Furthermore, described procedure reflects commonly used application-logic design of automation software (e.g. SCADA) based on IEC 61850 ACSIs.

V. CONCLUSION

Power systems transition towards the Smart Grids is challenging and difficult task with numerous potential pitfalls. The crucial prerequisite for fulfilling the Smart Grid vision is integration of devices and applications which are using standards-based semantic services. By recognizing IEC 61850 and IEC 61970 as two significant industrial automation standards, the power utilities have a possibility for gradual and faultless transition from traditional power systems towards the future-proof Smart Grid.

This article provides an overview of IEC 61850 and IEC 61970 main features. It is shown that integration efforts between these two standards can result in creating unified power system ontology and possibility to utilize standards-based semantic services at all Smart Grid levels. By creating subsystem-level services from IEC 61850 IEDs, which have been promoted as SOA-ready devices, a multitude of possible supervision and remote control frameworks can be created. As a case-study, standards-based virtual power plant semantic modeling principles are presented. Also, based on service-oriented and event-driven architecture design principles, specific procedure for wrapping high-level Smart Grid services has been proposed. Presented solutions demonstrate evolutionary capabilities of semantic-enabled utilities and stress importance of industrial automation standards in provision of next-generation power systems.

REFERENCES