Semantic Smart Grid Services: Enabling a Standards-Compliant Internet of Energy Platform with IEC 61850 and OPC UA

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Abstract—Large scale dissemination of power grid entities such as distributed energy resources (DERs), electric vehicles (EVs), and smart meters has provided diverse challenges for Smart Grid automation. Novel control models such as virtual power plants (VPPs), microgrids, and smart houses introduce a new set of automation and integration demands that surpass capabilities of currently deployed solutions. Therefore, there is a strong need for finding an alternative technical approach, which can resolve identified issues and fulfill automation prerequisites implied by the Smart Grid vision.

This paper presents a novel standards-compliant solution for accelerated Smart Grid integration and automation based on semantic services. Accordingly, two most influential industrial automation standards, IEC 61850 and OPC Unified Architecture (OPC UA) have been extensively analyzed in order to provide a value-added service-oriented integration framework for the Smart Grid.

Keywords: Smart Grid; energy automation; semantic services; IEC 61850; OPC UA; Internet of Energy

I. INTRODUCTION

The Smart Grid is envisioned as a future power system’s architecture that enables two-way flow of power and information among distinctive electric grid entities [1]. Contrary to traditional power systems, which are based on centralized control models and relatively static electric network topologies, the Smart Grid is characterized with decentralized management and dynamic electric network infrastructures [2].

One of the most influential changes stimulated by Smart Grid developments is large scale integration of heterogeneous, geographically dispersed, and intermittent power grid actors such as distributed energy resources (DERs), electric vehicles (EVs), and energy storage systems. However, these Smart Grid entities require scalable integration frameworks and optimized management techniques that exceed the capabilities of conventional automation solutions. A crucial prerequisite for future-proof Smart Grid automation is a technology-neutral and standards-compliant architecture that is capable to adapt for a variety of novel control models such as virtual power plants (VPP), microgrids or smart houses [3].

Service-oriented integration is one of the anticipated industrial automation paradigms [4]. It provides generic control patterns for distributed and heterogeneous device automation environments and it can also be easily integrated with enterprise-level applications. Moreover, one possible solution that could surpass the identified Smart Grid automation issues and create an extensible integration platform is the use of semantic services [3].

IEC 61850 [5] and OPC Unified Architecture (OPC UA)1 represent two most influential industrial automation standards relevant for service-oriented Smart Grid integration. Both specifications are based on separating automation architectures from implementation technologies in order to provide generic integration frameworks. Despite having some overlapping technical approaches [3], these two standards can be used together for creating value-added semantic services in the Smart Grid domain.

This contribution thoroughly analyses OPC UA and IEC 61850 in order to provide a standards-compliant approach enabling semantic Smart Grid services. It is shown how the proposed solutions provide groundwork for developing an Internet of Energy (IoE)2 [6] platform as one of the fundamental Smart Grid concepts.

The remainder of the paper is organized as follows: The next section provides an overview of relevant related work.

2 It has to be clarified how the term Internet of Energy is understood in the context of this work: Basically, IoE is used synonymously to the term Smart Grid and does not refer to the World Wide Web. It is a domain-specific instance of the Internet of Things that defines the overarching interconnection of devices mostly based on technologies like IPv6. Thus, IoE is a metaphoric concept describing the dynamic, highly interconnected, and multidimensional energy system of the future.
Section III gives an introduction to IEC 61850 and also outlines how this specification influences future Smart Grid developments. OPC UA capabilities and semantic services resulting from the IEC 61850 and OPC UA merging approach are analyzed in Section IV. Section V describes how to utilize the proposed service-oriented integration approach for managing novel Smart Grid control models and developing a standards-compliant IoE platform. Finally, the evaluation of the designed integration framework is discussed in Section VI.

II. SMART GRID INTEGRATION - MOTIVATION AND STATE-OF-THE-ART

Existing power systems are designated by a diversity of the interacting entities and a number of comprehensive control functions. However, the Smart Grid context brings an additional complexity layer to optimized power system management. Therefore, a seamless and standards-compliant integration is foreseen as crucial prerequisite for a successful and future-proof Smart Grid deployment [1], [2], [7].

The international standard IEC 61850 [5] has been recognized as a globally accepted solution enabling integration of heterogeneous devices and applications in the power system automation domain. It is identified as one of the fundamental components for reference Smart Grid architectures [8]. IEC 61850 is also one of the crucial IoE-platform building blocks. The IoE [6] reflects the convergent Smart Grid goal for providing pervasive and semantically designated energy entities that can be collectively supervised and/or controlled. Nevertheless, certain parts of the IEC 61850 definitions are inadequate to compete with the accelerated Smart Grid evolution [3]. This is most notable in selection of middleware technology that can be applied for the implementation of vertical communication in IEC 61850 systems. Despite providing an abstract definition for automation architecture [5], the only official implementation technology allowing supervision and remote control of field devices according to vertical communication (between field devices and applications) is the Manufacturing Message Specification (MMS) [5]. MMS [9] is a binary serialized message-oriented middleware optimized for automation applications. However, MMS is based on using the full Open Systems Interconnection (OSI)-model stack, it involves a complex application architecture and it also has a long learning curve [10]. MMS also lacks some of the crucial Smart Grid mechanisms such as device discovery and integrated security. For the above reasons, MMS is regarded as an inappropriate and over-engineered approach for novel Smart Grid control models such as, e.g., VPPs [11]. IEC 61850 also defines horizontal communication (between devices solely) [5] that is used for local automation functions but this is out of scope of this paper.

The OPC UA is the next-generation automation technology that is compliant to Web-based technologies and is truly platform-independent [12]. It provides generic and extensible automation mechanisms that can be used for a number of possible use cases and various automation environments [12]. There have been several contributions that demonstrate the applicability of OPC UA as a possible middleware mapping for IEC 61850 [3], [11], [13]. However, neither of the aforementioned papers provides a detailed analysis how to utilize abstract IEC 61850 application design requirements with OPC UA services. Merging IEC 61850 data semantics and OPC UA service-oriented integration principles defines a framework for creating semantic services that could streamline the overall Smart Grid deployment and provide a standards-compliant IoE-platform. VPPs are typical Smart Grid control models compliant to IoE-platform principles. VPPs are conceived as clusters of DERs grouped together in a controllable portfolio and acting as a single player in power system regulation and/or electricity markets [3]. Therefore, it requires a flexible and adaptable integration platform as provided by semantic Smart Grid services.

III. STANDARDS-BASED ENERGY AUTOMATION WITH IEC 61850

For years, power system automation was constituted from a diversity of vendor-specific automation solutions that operated as monolithic systems. There have been several attempts of developing standards-based solutions that would be unique and resistant to proprietary modifications. However, this problem was only partially solved until the introduction of IEC 61850. Contrary to other approaches that were focused on specifying telecontrol protocols, IEC 61850 defines an abstract automation architecture that is not constrained to a specific technology and can be easily extended for different distributed control subsystems. The main IEC 61850 features, semantic information modeling and abstract communication services, are presented in the following sections.

A. Power System Data Semantics

One of the general problems in energy automation was non-existence of standardized data semantics that could be used among heterogeneous power system devices. Therefore, IEC 61850 defines a specific information modeling architecture that guarantees semantic compatibility for field devices. Its meta-model is based on a hierarchically organized data structure and object-oriented design principles [5].

The top parent class is the Server, which represents a physical device, i.e., a device controller. The Server consists of one or more Logical Devices (LDs), i.e., virtual representations of devices intended for supervision, protection or control of automated systems. LDs are created by combining several Logical Nodes (LNs), which represent various device functionalities. LNs are an essential part of IEC 61850 data semantics. The first letter in the LN notation designates the functionality group (e.g., D - distributed energy resource, W - wind power plant, M - measurement), while the rest of the LN notation reflects the function name (e.g., DPVM – photo voltaic module, WROT – wind power plant rotor, MMXU – measurement unit).

Data Objects (DOs) are groups of Data Attributes (DAs). DAs are IEC 61850 system endpoints and are also granular LN elements. Both, DOs and DAs can be recursively nested. A typical DO instance consists of at least three DAs: val (the
data value), \( q \) (the data quality), and \( t \) (the data timestamp). Each DA has a data type assigned to it like Boolean (DAType).

The LN notation is standardized by LN classes, which are also defining the DOs of LNs. As many of the DOs of a LN class are optional, LNTypes define a more specialized usage of a LN class.

Common Data Classes (CDCs) enable creation of information models for domain-specific namespaces used by IEC 61850 applications.

From the application level perspective, DAs are categorized according to the specific functional use (e.g., control, configuration, measurement). Hence, DAs are designated by Functional Constraints (FC) indicating the use category. Also at application level, references to DOs and their subtypes can be organized into Data Sets (DS), which are used by IEC 61850 client applications.

B. Abstract Communication Services

Data exchange mechanisms defined in IEC 61850 are known as Abstract Communication Service Interfaces (ACSI) [5]. The IEC 61850 architecture manages two types of communication services: vertical (between devices and applications) and horizontal (between devices solely). This contribution is analyzing vertical integration aspects of IEC 61850 applications and therefore, only vertical ACSI services are further considered. The vertical ACSI services (ACSI\textsubscript{vertical}) are organized into several service models:

- **Association model (acsi\_asso)**: Services for managing bi-directional, connection-oriented information exchange between client and server.
- **Server/LD/LN/DO/DS models (acsi\_ldln)**: Services for browsing and editing information models and reading/writing data values.
- **Control model (acsi\_cont)**: Services enabling sending a command, i.e., changing state a of server process.
- **Set-Group-Control-Block (acsi\_sgcb)**: For one or more DOs, it enables settings selection between several predefined data values.
- **Report-Control-Block models (acsi\_rcl)**: Services enabling event-driven information exchange. They define mechanisms for reporting DO value changes to the clients based on the publish/subscribe paradigm.
- **Log-Control-Block model (acsi\_lcb)**: Services for storing historical DO values at the server level.

These ACSI\textsubscript{vertical} services can be used as standardized information interfaces for devices that are implemented as IEC 61850 servers. Thus, any IEC 61850 enabled client software can take full advantage of their remote control.

C. Implementing IEC 61850 Architectures

The development of vertical communication ACSI service models can be done with a variety of generic application-level middleware technologies. Currently, MMS has been successfully applied as IEC 61850 mapping in the substation automation domain. However, new control models require alternative mapping approaches, which not only fulfill ACSI prerequisites, but also provide additional benefits for facilitated Smart Grid integration. Therefore, in this contribution, OPC UA has been proposed as the state-of-the art industrial automation middleware, which could complement MMS and allow semantically-enabled, service-oriented integration for novel Smart Grid control models.

IV. OPC UA – UNIFIED AUTOMATION MIDDLEWARE

OPC UA is the successor of one of the most influential technologies in field of automation integration - the classic OPC. A study conducted among experts in 2003 showed that OPC was the favorite technology for exchanging data and linking processes for 78% of the production systems and Manufacturing Execution System (MES)-applications, 75% of the Human Machine Interface (HMI)-/Supervisory Control and Data Acquisition (SCADA)-systems, 68% of the process control system and Programmatic Logic Controllers (PLC), and 53% of the Enterprise-Resource-Planning (ERP)-systems [16]. Another study from 2008 with more than 3,500 responses exposed that 60% uses OPC often or always and that only 2% do not have knowledge about OPC [16]. In 2010, more than 20,000 OPC products were in use within different industry branches [16]. Opposite to classic OPC, which is based on deprecated proprietary technologies and has several application-dependent definitions, OPC UA provides a unified and vendor-independent solution. Similar to IEC 61850, OPC UA decouples meta-modeling concepts and data-exchange principles from actual implementation technologies. However, applying OPC UA as IEC 61850 middleware technology requires detailed analysis of the mapping approach.

A. OPC UA Meta-Modeling Concepts

Contrary to common middleware technologies that are being focused on data-exchange mechanisms only, OPC UA additionally defines specific meta-modeling principles optimized for automation environments. This feature allows the development of domain-specific information models and semantic consistency for entities interacting with OPC UA services [12]. The specific OPC UA information model is a set of semantically described data based on AddressSpace components. The basic AddressSpace unit is the Node comprising References and Attributes. The References define relationships with other Nodes (e.g., node A contains node B), while Attributes define Node characteristics (e.g., unique node id). All Nodes are specializations of the BaseNode class.

The Nodes are divided into several NodeClasses defining metadata for the AddressSpace components. These are as follows:

- **Object**: A Node that represents a physical or abstract element of a system. An Object comprises Variables and Methods and also allows relationships to other Objects.
- **ObjectType**: A Node that represents the type definition for an Object.
- **Variable**: A Node that contains a value. There are two types of variables, Properties (server-defined characteristics of Nodes) and DataVariables (content of an Object).
OPC UA Services can be implemented as UA Web Services and UA Native. UA Web Services use SOAP and several WS-* specifications that are running on top of HTTP(S), while UA Native only uses simple binary network protocols, which integrate certain security mechanisms and run directly on top of TCP/IP. The data encoding can be done in XML or using binary serialized data. These implementation approaches imply the fact that OPC UA is compliant to Web-based technologies and it provides an extensive framework for service-oriented integration.

D. Semantic Smart Grid Services

Integrating data-exchange procedures into a domain-specific semantic context provides a feasible environment for designing semantic services. These services support the development of context-aware and ontologically aligned applications. For Smart Grid use case, these types of services can be accomplished by merging IEC 61850 automation architecture principles with OPC UA capabilities. Therefore, besides developing an IEC 61850 data model with AddressSpace components it is also necessary to find functionally equivalent UA services to supplement the ACSI\textsubscript{vertical} service models. UA\textsubscript{services} and ACSI\textsubscript{vertical} have several overlapping modeling approaches and thus require a detailed mapping analysis.

1) Association Control: The first action for vertically integrated IEC 61850 applications is the creation of two-party associations, which enable reliable end-to-end information flow control. With OPC UA this can be fulfilled with help of Session Service Set (ua\textsubscript{sess}). These services provide a uniquely identified application layer connection establishment and can be easily mapped based on an one-to-one relationship with acsi\textsubscript{asso} (1).

\[
\text{acsi}_{\text{asso}} \cong \text{ua}_{\text{sess}} \tag{1}
\]

2) Information Model Management: acsi\textsubscript{inform} in IEC 61850 are dependant on the data structure levels. However, OPC UA defines a single NodeManagement Service Set (ua\textsubscript{nom}) for managing complete AddressSpaces. Subsets of the data model can be organized with the View Service Set (ua\textsubscript{v}). Therefore, a combination of the three aforementioned UA\textsubscript{services} services fulfills the IEC 61850 information modeling requirements (2).

\[
\text{acsi}_{\text{inform}} \subseteq (\text{ua}_{\text{nom}} \cup \text{ua}_{\text{v}} \cup \text{ua}_{\text{attr}}) \tag{2}
\]

3) Device Management: Complex control block structures responsible for sending control commands (acsi\textsubscript{cmd}) and editing device settings (acsi\textsubscript{poch}) are directly influenced by writing specific data values. Therefore, these ACSI\textsubscript{vertical} service models are mapped to ua\textsubscript{attr} (3).

\[
(\text{acsi}_{\text{cmd}} \cup \text{acsi}_{\text{poch}}) \cong \text{ua}_{\text{attr}} \tag{3}
\]
4) Event-Driven Data-Exchange: IEC 61850 differentiates two types of event-driven data-exchange mechanism: 
\[ \text{acsir}_{cb} \] for enabling instantaneous event delivery based on publish/subscribe paradigms and 
\[ \text{acsil}_{cb} \] for postponed retrieval of event occurrences relevant to post-disturbance analysis. However, each of these ACSI service models can be implemented with combination of two OPC UA services sets. The MonitoredItem Service Set (\( \text{ua\_monit} \)) allows clients to create, modify, and delete MonitoredItems (items used to monitor Attributes for value changes) while the Subscription Service Set (\( \text{ua\_sub} \)) allows clients to create, modify, and delete Subscriptions (collections of MonitoredItems, which in case of a value change send a Notification to the client). The combined usage of these two service sets fulfills all functional requirements for vertical event-driven communication in IEC 61850 systems (4), (5).

\[ \text{acsir}_{cb} \cong (\text{ua\_monit} \cup \text{ua\_sub}) \] (4)

\[ \text{acsil}_{cb} \cong (\text{ua\_monit} \cup \text{ua\_sub}) \] (5)

5) Additional Native OPC UA Services: Besides the services mentioned in the previous sections, OPC UA also supports service sets, which do not directly reflect IEC 61850 application functional requirements but can be used as value-added features of novel Smart Grid control architectures. These are:

- **Discovery Service Set (\( \text{ua\_disc} \))**: It enables discovery mechanism for OPC UA-compliant servers. In the Smart Grid domain these could be, e.g., DERs or smart meters.

- **Method Service Set (\( \text{ua\_meth} \))**: It is used for starting executions of specific pre-programmed logic on OPC UA servers.

- **Query Service Set (\( \text{ua\_quer} \))**: Enables retrieval of AddressSpace subsets based on filter criteria.

- **SecureChannel Service Set (\( \text{ua\_sech} \))**: Provides the capability of secure communication among OPC UA entities (enables confidentiality and integrity for exchanged messages).

Relationships between ACSI service models and OPC UA Services are shown in Fig. 1.

The presented service mapping analysis shows that UA services completely fulfill ACSI vertical requirements and moreover, OPC UA provides additional beneficial functionalities from of UA services that are not directly mapped to IEC 61850 ACSI. The described mapping approach enables Web-based and service-oriented integration of heterogeneous power system entities what could significantly facilitate the Smart Grid deployment. Integration issues and use cases based on the proposed mapping are discussed in the following chapters.

V. PERVERSIVE SMART GRID ENVIRONMENTS - INTERNET OF ENERGY

Large scale deployment of diverse power grid actors with capability of two-way flow of energy and information has provided unforeseen ecology of prosumers (Smart Grid entities that are both producers and consumers of electricity) [17] such as electric cars or smart houses. Along with escalating the number of integrated DERs and smart meters, prosumers define pervasive Smart Grid environments, i.e., electric power grids with the capability to fully utilize Smart Grid benefits such as optimal power flow, self-healing network ability or economic dispatch of energy. Divergent characteristics of entities included in pervasive Smart Grid environments require the existence of a universal approach for remote control and supervision of field devices in order to enable their optimized management [3]. The IoE is envisioned as an overlay network for electric power grid, fulfilling these requirements [6]. It is defined as a mashup of Smart Grid entities that share common methodologies for addressing, modeling, and exchanging information among devices and applications. However, the IoE requires concrete technical solutions that fulfill the aforementioned requirements in a technology-neutral and vendor-independent manner. In this contribution, semantic services based on OPC UA and IEC 61850 principles are proposed as a suitable standards-compliant platform for enabling the IoE.

A. Standards-Compliant Internet of Energy Platform

Modeling semantics of power grid entities with OPC UA and IEC 61850 provides groundwork for a unified Smart Grid ontology [13]. Universal data exchange services for semantically consistent Smart Grid entities define a flexible (capable of dealing with the highly dynamic future energy management systems) and scalable platform for IoE.
management. OPC UA allows decentralized integration of novel Smart Grid control models as well as fine-grained manipulation of relevant information. Architectural layers of an OPC UA-compliant IoE platform are shown in Fig. 2:

1) Electric Grid: It is defined as a group of interconnected power system entities, which exchange electric power. It involves different actors relevant for generation, transmission, and distribution of electric power such as hydro and wind power plants, DERs, power lines, electric vehicles, and electricity consumers. Here, the physical product electricity is exchanged.

2) Communication Network: This is a set of communication equipment, which enables bi-directional exchange of data among power system entities. Regardless of the communication medium (fiber optics, serial links, GPRS, power line communications) its primary goal is reliable data transfer. Compared to the electric grid, here, only digital data is exchanged.

3) Ontology Layer: Refines data exchanged via communication networks by adding domain specific semantic meaning. It provides AddresSpace definitions for underlying physical equipment based on IEC 61850 definitions.

4) Services Layer: Allows generic management capabilities for semantically described data and it enables complex data interactions for geographically dispersed devices.

The two lower layers provide IoE infrastructural prerequisites while the two upper layers directly utilize OPC UA capabilities, i.e., information modeling and semantic services. An overview of IoE management principles based on OPC UA and IEC 61850 benefits are analyzed in a VPP control use case.

VI. STANDARDS-COMPLIANT IOE PLATFORM USE CASE: CONTROLLING VIRTUAL POWER PLANTS

The VPP is a promising concept for future Smart Grids. On a high level perspective, the VPP combines different generation, storage, and consumption units by management applications in order to optimize the overall system.

Fig. 3 outlines a generic VPP system. Controllable loads can be large cooling or heating storages, both managing a large amount of the consumed energy for thermal storage processes. The controlled temperatures have to be in a certain range so that in case of the cooling storage excessively produced energy can be used to cool down until the lower limit is reached. Generation can be realized by wind power plants, solar power plants or combined heat and power (CHP) units. The storage devices can be batteries and electric vehicles. A communication based on an OPC UA architecture using IEC 61850 semantics for both, services and data models allows exchanging data seamlessly, automated, and comprehensively down to the field layer compliant to the proposed IoE platform. Furthermore, it decreases the integration costs of further services (no more mappings are necessary). Another important aspect is that this architecture does not restrain other systems. Thus, other protocols (e.g., MMS) and standards (e.g., IEC 61970/61968) may be used complementarily.

A. Use Case: Simulated VPP Model

From the OPC UA perspective, the VPP is a group of several OPC UA servers with AddressSpaces compliant to IEC 61850 semantics and providing its capabilities through aggregated OPC UA server interface.

Fig. 4 provides an overview how the generation and storage units can be modeled according to IEC 61850 semantics and ACSI services required for remote VPP control. Detailed description of VPP semantics can be found in [5].

For the implementation, the Quickstarts and their underlying OPC UA .NET stack that are both provided by the OPC Foundation³ have been chosen.

Applying the introduced mappings leads to simulated servers that can be accessed by OPC UA clients. Each of the components was modeled as OPC UA server and their behavior is simulated based on real world data. OPC UA clients have been implemented as prototypes in order to call the services.

Fig. 4 outlines the complexity of VPP information models and ACSI vertical service models interactions required for VPP remote control. However, common ACSI vertical capabilities are inadequate to automatically integrate an additional DER device into the dynamical Smart Grid control model such as a VPP. The following section demonstrates how this can be done with help of additional UA services that are not directly mapped to IEC 61850 ACSI vertical service models.

B. Use Case: Integrating DER in VPP

1) DER Registration: The first step for the DER integration process is its registration started by internal request RegisterDER(). On the communication interface this request is mapped to RegisterServer() that is a native OPC UA service from \( \text{ud}_{\text{der}} \). This service results in providing Discovery Server with OPC UA server Endpoints (physical device address on communication network, e.g., IPv6 address). This service is solely used by DER devices.

2) Finding DERs: This service is started by the VPP application when trying to integrate another DER device into its controlling portfolio. It is mapped into several consecutive OPC UA service calls from \( \text{ud}_{\text{der}} \) and \( \text{ud}_{\text{acsi}} \). FindServer() responds with descriptions of available DERs and their discovery Endpoints. GetEndpoints() returns Endpoints descriptions supported by the OPC UA server and information required for establishing a session. CreateSession() and ActivateSession() are used to create and activate a uniquely identified session between OPC UA client and server. Positive responses from these services finalize the DER discovery process initiated by the VPP application.

3) Obtaining DER Semantics: In order to utilize Smart Grid services in a semantically enabled environment it is necessary to obtain data model descriptions from OPC UA servers. This is done via the Browse() service, which retrieves all supported AddressSpace elements to the requested server. With the standardized data model provided by this service any high-level application is capable to manage DER data in a flexible and vendor-independent manner.

4) Event Delivery Mechanism: Smart Grid control models, such as VPP, depend on data values of specific information model subset. This data is necessary to fulfill control model function goals (e.g., optimized power production), which are natively event-driven. The first step in obtaining events is a
subscription request for a specific data subset. This is done by consecutive calls of CreateMonitoredItems() where MonitoredItems are OPC UA structures used to monitor attributes for value changes and CreateSubscription() that buffers events for that specific MonitoredItem. Process events are spontaneously pushed by the DER device to the OPC UA server. Events are retrieved by requesting the OPC UA server to send all accumulated events with the Publish() service.

5) DER Management: Changes of the server side process are provoked by either sending control commands or changing specific DER setpoints. In both cases the requests are mapped as a Write() request to specific AddressSpace attributes.

The described service invocation process demonstrates how additional OPC UA services (e.g., ua_async) that are out of scope of ACSIs requirements provide significant value-added features in managing complex Smart Grid control models.

VII. CONCLUSION

The power system’s transition towards the Smart Grids is a complex and challenging task. The seamless integration of novel Smart Grid control models such as VPPs, microgrids, and smart houses require standards-based and adaptable technical solutions. The IoE is a promising new device integration approach applicable to the Smart Grid domain that could fulfill these requirements.

This paper introduces a standard-compliant approach for creating an IoE platform in order to support Smart Grid integration and automation requirements by combining power system domain standards such as IEC 61850 with OPC UA as middleware technology.

The proposed IoE architecture is based on a layered modeling approach. The electrical grid and the communication network are the fundamental layers while the ontology layer and service layer are top layers fully utilizing OPC UA capabilities. This approach is exemplified by analysing a VPP control concept and dynamic DER integration principles. Also, a proof-of-concept application prototype for controlling VPPs has been developed in order to demonstrate the capabilities of the proposed solution. It is shown that additional OPC UA services such as ua_async provide significant added-value features for managing complex Smart Grid control models such as VPPs and microgrids.

By using OPC UA as a middleware that provides generic automation services and adaptable information modeling capabilities, the presented approach allows a simplified integration of a variety of Smart Grid applications and novel control models with help of semantic services. The ontology layer allows a streamlined integration of a variety of data sources with dedicated information models into a presented Smart Grid integration framework by providing standards-based semantics for the service layer.

The proposed IoE platform is flexible, adaptable, and scalable, thus being a promising technology candidate that could accelerate DER integration, support a variety of novel control models, and improve interoperability in a semantic-enabled Smart Grid by utilizing standards-based technologies.

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