A device-level service-oriented middleware platform for self-manageable DC microgrid applications utilizing semantic-enabled distributed energy resources

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Abstract

Dynamic and adaptable integration of Distributed Energy Resources (DERs) into novel power system assets, such as microgrids, is one of the key prerequisites for accelerated Smart Grid deployment. By using standardized network interfaces and semantic definitions for remotely controllable DERs, it is possible to develop intelligent microgrid applications capable of dealing with dynamic loads and intermittent DER power production. IEC 61850 standard has been accepted as one of the prime movers of successful and interoperable Smart Grid communication and integration. Although primarily being applied to the substation automation, IEC 61850 now provides semantic definitions for DER devices allowing it to be applied to expert microgrid application development. The current IEC 61850 middleware definition cannot cope with certain Smart Grid requirements such as support for autonomous microgrid applications with DER plug-and-play capability. These issues could be solved by integrating the device-level Service Oriented Architecture (SOA) paradigm into IEC 61850 applications. Developing a device-level SOA middleware platform based on IEC 61850 principles could significantly facilitate standards-compliant DER integration and accelerate microgrid deployment. A new middleware platform for microgrid applications is proposed. It is based on integrating device-level SOA design principles into IEC 61850 applications in order to fulfill dynamic microgrid management requirements.

Keywords:
Smart Grid
Microgrid
Middleware
Semantic integration
Device-level SOA
IEC 61850

1. Introduction

Electrical power grids of the future, also known as Smart Grids [1], introduce numerous challenges and novelties into all of the elements of traditional power systems. The indispensable Smart Grid goal of achieving a two-way flow of power and information is hampered by the use of non-interoperable and proprietary communication systems. Hence, one of the key prerequisites of successful Smart Grid deployment is streamlined integration of standards-compliant devices and applications. International standard IEC 61850 [2] is foreseen to be a solution providing extensible Smart Grid integration, as well as a communication architecture based on vendor-independent and technology-neutral principles. However, the current definition of IEC 61850 is tightly-coupled with the integration of substation automation characterized by relatively predetermined management principles and static configurations. Novel Smart Grid assets, such as microgrids [3] and virtual power plants (VPPs) [4], require dynamic reconfiguration capabilities for system entity interaction. Although IEC 61850 supports semantic definitions for DERs and, therefore, can be applied to microgrid applications, there is still a lack of support for dynamic and self-managed microgrid features such as automatic DER discovery, semantic interpretation of DER capabilities and DER integration into microgrid applications without human intervention. Consequently, there is a strong need for finding a suitable technical solution which complements the current IEC 61850 definition with functionalities which enable the development of adaptable expert applications to support dynamic management of novel Smart Grid assets such as microgrids.

The solution proposed in this paper aims at fulfilling direct current (DC) microgrid self-management requirements by integrating device-level Service Oriented Architecture (SOA) [5] design principles into IEC 61850-based devices and applications. SOA is a widely accepted application integration principle in the enterprise domain and one of the envisioned future integration paradigms for real-time industrial automation [5, 6].

This paper provides a detailed analysis of IEC 61850 application architecture requirements for SOA-based integration and introduces middleware platform capabilities which utilize semantic-enabled DERs in order to create self-manageable microgrid...
applications. A multi-criteria comparative analysis of the state-of-the-art device-level SOA technologies and current IEC 61850 middleware capabilities is presented in order to identify the key features required by self-manageable microgrid applications. As a result of the analysis, a novel middleware platform which integrates both Devices Profile for Web Services (DPWS) [7] and OPC Unified Architecture (OPC UA) [8] design principles into IEC 61850 applications is proposed. The presented solution provides a service-oriented and semantic-enabled DER integration framework which is compliant with industrial middleware standards and can significantly contribute to the development of dynamic and self-manageable microgrids.

The rest of the paper is organized as follows. The next section provides an overview of the related work while Section 3 gives a short introduction to the IEC 61850 standard. Section 4 identifies IEC 61850 application design issues resulting from microgrid integration requirements and provides results from the comparative analysis of device-level SOA technologies. The co-existence of DPWS and OPC UA technologies in the proposed microgrid middleware architecture is presented in Section 5. A description of the developed proof-of-concept prototype application and the microgrid simulation results are analyzed and presented in Section 6. Finally, a conclusion is given in the last section.

2. Microgrid middleware – motivation and state-of-the-art

2.1. The Smart Grid vision

The Smart Grid involves a significant number of heterogeneous and geographically dispersed actors with intermittent energy sources such as DERs, energy storage systems and wind power plants [1]. Integration of these Smart Grid entities has resulted in novel system management architectures, such as microgrids [3], while introducing new solutions for intelligent energy control [9,10].

IEC 61850 provides a standardized communication interface for remotely controlled entities in a technology-neutral manner while separating data semantics from data exchange services [11]. Therefore, IEC 61850 definitions can be easily extended to the overall Smart Grid domain as well as support the microgrid concept. Microgrids are envisioned as novel power systems architectures which provide value-added features for coordinated control of groups of DERs [12]. Microgrids are typically requested to be able to work in both grid-connected and island modes, each of which can impose specific demands on the system. If grid-connected, the microgrid might have to support the main grid with ancillary services, while in the island mode the load supply should be done without interrupting the power supply.

The variable nature of renewable energy resources, which are an integral part of the microgrid, relies on hard-to-predict natural phenomena. Hence, energy storage systems, such as fuel cells, flywheels, or batteries, must also be included to achieve adequate control.

Recently, papers [13,14] have dealt with IEC 61850-based microgrids. These papers are focusing on specific applications of IEC 61850 standard in microgrid domain. Paper [13] is based on modeling centralized protection systems for microgrid based on IEC 61850 data model definitions. Paper [14] demonstrates capabilities of using IEC 61850 for controlling active and reactive power for utility connected microgrid. However, none of the aforementioned papers deals with microgrid middleware requirements and the problems of dynamic DER integration using standards-based vertical communication.

2.2. Industrial service-oriented middleware technologies

For years power system automation was based on specialized vertical communications and single-purpose systems. The paradigm shift from centralized and tightly-coupled systems to decentralized and adaptable automation architectures [15] has been accompanied by new software integration techniques and standards-based communications. One of the most prominent design paradigms for next-generation automation applications is based on SOA principles [5,16]. Despite the fact that SOA originates from the enterprise domain, it has been successfully applied to real-time applications [6]. SOA is based on decomposing the system into a set of services which reflect process functions. Services are defined as autonomous, platform-independent entities which can be described, published, discovered and assembled [17]. The SOA paradigm is considered an effective approach for building integrated, heterogeneous and distributed applications.

Introducing the SOA paradigm into power system automation systems enables the reuse of existing solutions, expansion of the application domain and creation of generic automation service components. Furthermore, one of the outcomes of SOA-based automation has been the development of embedded, device-level SOA technologies [5,18]. Two of the most influential device-level SOA technologies which have been developed within the framework of industrial consortium research projects and standardization bodies are DPWS [7] and OPC UA [8]. Despite having competitive technical approaches, their cooperation is foreseen as a feasible solution to provide significant value-added features for service-oriented industrial automation [18,19].

2.3. Device-level SOA for microgrids

Although IEC 61850 is a globally accepted power system automation approach, its current definition and integration aspects cannot compete with dynamic and reconfigurable Smart Grid architectures such as microgrids. Common IEC 61850-based substation automation applications are based on preconfigured communicating entities (e.g. protective relays and station computers) and a predetermined list of exchangeable process data. Microgrids, however, require advanced capabilities which can dynamically add/remove DERs from their control portfolio and possibility subscribe/unsubscribe to relevant process data during run-time. This problem can be solved by introducing device-level SOA design principles into IEC 61850 applications. There have been several approaches for complementing IEC 61850 with device-level SOA capability including DPWS [20], OPC UA [21] and RESTful services [22]. However, the approach presented in this paper is an integral solution which utilizes benefits of the combined usage of DPWS and OPC UA in IEC 61850 applications, as well as standards-based DER semantics, in order to support self-manageable microgrid applications. Basic concepts of combined DPWS and OPC UA usage are presented in the paper [23], while our paper provides in-depth analytical approach for developing middleware architecture for optimized microgrid control.

3. IEC 61850 – A Smart Grid automation architecture

IEC 61850 [2] standard describes automation architecture which defines requirements for vertical and horizontal communication services as well as standardized data semantics used for controlling and managing field devices. The following chapters provide an overview of the main IEC 61850 features.
3.1. Semantic-enabled Smart Grids

One of the essential novelties of IEC 61850, in comparison with other approaches, is the use of standardized data semantics for subsystem automation functions. The semantic data descriptions within IEC 61850 have been optimized for centralized and hierarchically organized supervisory control applications. The data model structure is object-oriented, containing information relevant for process automation [4,11].

Relationships between the IEC 61850 data model classes are shown in Fig. 1. The top parent class is the Server which represents a physical device, i.e. is a device controller. A single Server can consist of one or more Logical Devices (LDs), i.e. virtual representations of real devices (e.g. circuit breaker, DER, inverter). LDs are combinations of Logical Nodes (LNs) which represent specific device functionalities. LNs are integral IEC 61850 semantic components based on four letter designations. The first letter in the LN notation defines the functionality group (e.g. D – distributed energy resource) while the rest of the LN notation reflects the function name (e.g. PVM – photo voltaic module).

Granular LN elements are Data Objects (DOs) which consist of several Data Attributes (DAs). DAs are leaf elements in the IEC 61850 data model structure and are basically systems endpoints involved in automation. The fundamental DAs are the process data values, data quality and data timestamps. Both DAs and DOs can be recursively nested.

From an application-level perspective, DAs are categorized according to their specific functional use (e.g. control, configuration, measurement). Hence, DAs are designated by a Functional Constraint (FC) indicating its category of use. Also, at the application-level, references to DOs and its subtypes can be organized into Data Set (DS) which are used by the IEC 61850 client application to optimize communication bandwidth usage.

The described modeling concepts are easily applicable to a number of Smart Grid entities. Existing IEC 61850 definitions [2] cover substations, hydro power plants, DERs and inverters. It is expected that in the near future these definitions will also be expanded for energy storage systems, steam and gas turbines, electric vehicle supply stations, and smart homes/buildings.

3.2. Data-exchange models

Communication between IEC 61850 applications and devices is based on technology-neutral specifications known as Abstract Communication Service Interfaces (ACSIs). ACSIs are formed as a set of rules and state machines defining data exchange procedures and mechanisms [11]. They include definitions and interface requirements for horizontal communication (between IEC 61850 devices) and vertical communication (between IEC 61850 devices and applications).

Horizontal communication in IEC 61850 systems is based on the peer-to-peer paradigm and a publish/subscribe mechanism. It includes the following ACSI service models:

- **Generic substation event model**: Responsible for transmitting Generic Object Oriented Substation Event (GOOSE) messages which convey information about signal state values. These messages are mostly used for various low-level automation functions such as interlocking and protection at the substation level.
- **Transmission of sampled values model**: Enables multicast and unicast transmission of digitalized measurements of process data values which are sampled at a certain rate.

The ACSI service models required for vertical communication are based on the client/server paradigm and include the following:

- **Association model**: Responsible for managing bi-directional connection-oriented data exchange between communicating servers and clients.
- **Server/LD/ LN/DO/DS models**: Enable browsing and editing of the IEC 61850 semantic data model and reading/writing endpoint data values.
- **Setting-Group-Control-Block model**: Enables selection of the settings for one or more DOs among several predefined data values.
- **Control model**: A mechanism for sending control commands, i.e. changing the state of the server process.
- **Log-Control-Block model**: Stores historical DO values at the server level.
- **Report-Control-Block models**: Enable event-driven data exchange. Defines a mechanism for reporting DO value changes to the IEC 61850 clients in accordance with the publish/subscribe paradigm.

Horizontal ACSI service models are primarily used for real-time automation functions in local area networks (LANs) while vertical ACSI services are used for soft real-time automation applications in wide area networks (WANs). Network data traffic resulting from horizontal ACSIs is characterized by cyclic data bursts, while for vertical ACSIs it is mostly event-driven. Vertical ACSI service models allow for remote control of IEC 61850 devices and provide high flexibility for developing customized automation-centric and enterprise-level IEC 61850 applications.

This paper focuses on the generic middleware platform required for vertical communication and semantic-enabled DER integration. In this context, it is presumed that low-level automation requirements, such as local protection logics, are preconfigured and that vertical ACSI service models are used as the generic service-level framework for developing self-manageable and centrally controlled IEC 61850-based microgrid applications. Consequently, only vertical ACSI service models will be discussed further in the text.

4. Microgrid middleware requirements analysis

Although the implementation of IEC 61850 vertical communication ACSI service models can be achieved using a variety of general-purpose middleware technologies, currently there is only one official and standardized middleware mapping. This is the Manufacturing Message Specification (MMS) mapping [24]. MMS-based implementations of IEC 61850 vertical communication systems have been successfully applied to the substation automation domain for years, substantially contributing to the accelerated dissemination of IEC 61850 systems. However, some specific MMS
features make it difficult to apply outside the substation automation domain and it is not optimized for novel Smart Grid architectures such as microgrids.

The IEC’s Technical Committee 57 (TC57) has started new standardization efforts aimed at finding a suitable technical solution to extend the IEC 61850 standard to support new Smart Grid use cases. One of the TC57 requirements is finding a Web service-based mapping for vertical ACSI services. In this paper, we propose a potential vertical ACSI mapping solution which could fulfill the TC57 requirements and could be applicable to self-manageable microgrid applications. To support this proposal, an analysis and comparison is provided of state-of-the-art Web-based industrial middleware technologies and MMS.

4.1. Microgrid middleware requirements

By analyzing [11], the basic set of application middleware requirements for vertical ACSI service models can be expressed as the following:

- Distributed application design capability;
- Soft real-time performance;
- Device-level integration;
- Event-driven data exchange;
- Platform-independent and standard-compliant.

These requirements completely fulfill the functional scope of IEC 61850 applications commonly used in the substation automation domain. However, the extension of IEC 61850 to increasingly deployed Smart Grid entities such as DERs, energy storage systems and smart meters introduces a new set of original design requirements for automation applications [4,21]. The new requirements reflect the general objective of applying the IEC 61850 architecture to self-manageable microgrids. These novel middleware design requirements are as follows:

- Support for embedded applications with enterprise-level integration capability;
- An event-driven service-oriented architecture;
- Semantic-enabled data exchange;
- Dynamically reconfigurable and scalable applications;
- Web-based compatibility;
- Plug-and-play DER capability;
- Short time-to-market development.

These requirements outline the complexity of interactions among microgrid entities and establish the foundations of future-proof automation application design outside of substations. The IEC 61850 architecture is defined in an abstract manner and, hence, it is generic enough to be complemented with a suitable middleware platform in order to fulfill the identified requirements. In this paper, we show how integrating device-level SOA capabilities into future IEC 61850 applications can significantly contribute to fulfilling the aforementioned middleware requirements.

4.2. Manufacturing Message Specification (ISO 9506)

MMS [25] is application-level message-oriented middleware with binary serialized data encoding. It is optimized for low bandwidth networks and distributed soft real-time automation applications. Although it is used in current IEC 61850 systems, MMS does not support meta-modeling required by semantic-enabled applications. Alternatively, this issue is solved by introducing a delimiter character for process item address definition. A major drawback of MMS is its complexity, which comes from using the OSI stack and, thus, involves a long learning curve and lengthy from-scratch development. In addition to this, currently there is no fully functional and freely available open-source MMS stack. Another significant drawback of MMS is its lack of security mechanisms which is an essential functional requirement in fully integrated Smart Grids. MMS-based applications require a set of preconfigured settings (e.g. network address, OSI stack parameters) and, thus, are not able to the support plug-and-play capability required for dynamic DER integration.

The aforementioned issues make MMS-based IEC 61850 application development unnecessarily difficult, over-engineered and inadequate with respect to fulfilling the microgrid management requirements. These and similar issues have motivated IEC TC57 to search for a suitable middleware platform which would enable the application of IEC 61850 principles outside the substation automation domain. This paper analyses the potential middleware solutions for a device-level SOA platform for IEC 61850 applications. The results of this research are submitted to the IEC TC57 work group responsible for developing new middleware mapping.

4.3. Device Profiles for Web Services

DPWS [7] is a specific profile of Web service protocols enabling SOA capabilities at resource constrained devices. It is partially based on the Web Services Architecture (WSA) from [26] which enables creating highly-modular and incrementally-integrated protocol stacks. Its main difference with respect to WSA is that DPWS does not require a centralized service repository but uses multicast service discovery as an alternative.

4.3.1. The protocol stack

The DPWS protocol stack is based on combining several WS- specifications as shown in Fig. 2. These are as follows:

- WS-Addressing: Provides an addressing mechanism for Web Services in a transport-neutral manner. It decouples SOAP from its underlying protocol and supports asynchronous message exchange.
- WS-Discovey: A discovery protocol based on UDP and multicast. It is used by devices to advertise themselves, as well as to discover other devices.
- WS-MetadataExchange: Defines data-types and operations for the dynamic retrieval of device and services metadata such as WSDL or XML schema definitions.
- WS-Eventing: A protocol for managing the publish/subscribe mechanism and asynchronous event-driven data exchange.
- WS-Security: A flexible and feature-rich SOAP extension providing additional security for Web Services. It specifies how security, confidentiality and various security token formats can be integrated into SOAP messages.
- WS-Policy: A set of specifications that describes the capabilities and constraints of various policies (e.g. security, Quality of Service) which can be advertised or required.

![Fig. 2. The DPWS protocol stack.](image-url)
The DPWS protocol stack addresses SOA mechanisms which enable service addressing, dynamic discovery, self-description and event notification for heterogeneous networked devices. Furthermore, it can be regarded as a transport platform for integrating a variety of customized, application-level services.

4.3.2. DPWS as IEC 61850 middleware

A strong argument for using DPWS for Smart Grid automation is the availability of a number of open source toolkits and significant community support for its realization resulting from industrial research projects [27,28]. However, in order to implement the IEC 61850 architecture based on the DPWS protocol stack it is necessary to additionally develop customized application-level services which fulfill ACSI functional requirements. An example of a possible solution is the Web service mapping found in [29]. However, tight coupling of IEC 61850 systems with new special-purpose Web Services introduces new integration issues for existing automation solutions. Another main drawback of DPWS is its lack of meta-modelling capability what is a critical IEC 61850 requirement. In order to extract semantic data from the DPWS server, a generic Web Service client has to analyze XML schema documents and resolve data structures.

For the above reasons, DPWS can mainly be regarded as a suitable solution for providing lower-layer mechanisms and transporting profiles in the device-level SOA approach in the context of IEC 61850, but it does not offer a complete solution for aggregate application-level mapping.

4.4. OPC Unified Architecture

OPC UA [8] is a state-of-the-art device-level SOA technology and a successor of one of the most influential technologies in the field of industrial automation, called OPC. In contrast to OPC, which is based on Microsoft’s COM/DCOM, OPC UA is truly platform-independent and based on open standards. Similar to the IEC 61850 concept, OPC UA defines a set of application-level services which are independent of implementation technology while equipped with information modeling capability.

4.4.1. OPC UA services

These services are based on defining request and response parameters that are sent between the client and the server. OPC UA services are logically grouped into service sets that enable server discovery, session manipulation, address space management and, lastly, polling-based and event-driven data exchange. The services can be implemented as UA Web Services and UA Native services. UA Web Services are based on a set of WS-* specifications similar to DPWS as described in [18], while UA Native uses a simple binary network protocol which integrates certain security mechanisms and runs directly on top of TCP/IP.

4.4.2. OPC UA meta-modelling

The second important feature of OPC UA is its meta-modelling mechanism based on the AddressSpace concept. AddressSpace elements are fundamental in creating information models based on collections of semantic data which the OPC UA server provides to OPC UA clients.

The basic AddressSpace unit is a Node comprised of References and Attributes. References define its relationships with other Nodes (e.g. node A contains node B), while Attributes define Node characteristics (e.g. unique node identification). All Nodes are instances of the BaseNode class. Nodes are divided into several Node-Classes which define metadata for AddressSpace components as shown in Fig. 3. These are as follows:

- **Object**: A Node representing a physical or abstract element of a system. An Object comprises Variables and Methods and allows relationships to other Objects.
- **ObjectType**: A Node representing the type definition of an Object.
- **Variable**: A Node containing a value. There are two types of variables, Properties (server-defined characteristics of Nodes) and DataVariables (content of an Object).
- **VariableType**: A Node representing the type definition of a Variable.
- **Method**: A callable software function that is a component of an Object. Similar to the class method in object-oriented programming.
- **DataType**: Defines the data type of a Variable.
- **ReferenceType**: A Node representing the type definition and semantics of a Reference. ReferenceTypes are divided into hierarchical (used for constructing data hierarchies) and non-hierarchical (used for defining non-hierarchical relationships).
- **View**: A specific subset of the AddressSpace that is of interest to the OPC UA client. Classes Object, Variable and Method are key NodeClasses that enable object-oriented system design. Information model structuring is done with Objects, ReferenceTypes and Views, thus providing several information model hierarchies for the same OPC UA server.

4.4.3. OPC UA as IEC 61850 middleware

The main features of OPC UA fulfill all the middleware requirements of the IEC 61850 architecture. The ACSI concept is very similar to OPC UA Services, while an AddressSpace can be used for modeling IEC 61850 data semantics. Additionally, OPC UA specifies several protocol stacks defining the usage of individual implementation technologies. Nevertheless, OPC UA has certain issues which prevent it from being completely compliant with IEC 61850 principles, the most notable of which is the event-driven data exchange mechanism. OPC UA enables notification-based communication by combining the MonitoredItem Service Set and the Subscription Service Set. Although designated as event-driven, data exchange based on these services is done according to a periodic request/response pattern and basically polls notification queues according to subscriptions. Therefore, the data exchange is not really event-driven and asynchronous which is one of the crucial scalability requirements for self-manageable microgrid applications. This is caused by the selection of lower-layer WS-* specifications for OPC UA which do not support asynchronous HTTP-based data exchange. In the case of DPWS, this feature c by using n be realized by using WS-Eventing.

Despite the aforementioned issues, IEC 61850 can partially be mapped to OPC UA as shown in [21]. A crucial prerequisite is
Finding functionally equivalent OPC UA Services which can fulfill application-level requirements of ACSI service models.

5. Service-oriented device integration with IEC 61850

Integrating device-level SOA design principles into self-manageable microgrid applications requires an implementation technology capable of fulfilling all IEC 61850 architecture requirements. Table 1 shows the results of a multi-criteria comparative analysis of DPWS, OPC UA and MMS.

Although none of the previously analyzed device-level SOA middleware technologies individually fulfill the requirements, the DPWS and OPC UA technologies together satisfy the complete requirements list. Merging these two technologies has been previously proposed in the literature [18, 19]. This paper focuses on designing an adequate Web-based middleware platform for future IEC 61850 systems such as self-manageable microgrids. Therefore, the following DPWS and OPC UA benefits were taken into account: extensibility of the DPWS protocol stack, standard-compliant OPC UA application-level services and AddressSpace meta-modeling capability. The following sections give a proposal on how to utilize merged DPWS and OPC UA components.

5.1. Converged device-level SOA middleware for IEC 61850-based microgrids

The proposed converged middleware architecture for IEC 61850 systems outside of the substation automation domain is based on integrating OPC UA Services into the DPWS protocol stack.

DPWS middleware distinguishes two basic entities: a Hosting device and Hosted services. The Hosting device is used for hosting one or several Hosted services which provide various application functionalities. The Hosting device also supports the built-in DPWS services which allow dynamic device discovery (WS-Discovery), service self-description (WS-MetadataExchange) and event-driven data exchange (WS-Eventing). In order to develop an IEC 61850 application with DPWS, ACSI functionalities need to be implemented as Hosted services. OPC UA Services are application-level services which can be integrated as Hosted services of DPWS.

Table 1: Multi-criteria comparison between MMS, DPWS and OPC UA.

<table>
<thead>
<tr>
<th>Feature</th>
<th>MMS (ISO 9506)</th>
<th>DPWS</th>
<th>OPC UA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Web service-based</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Transport profile</td>
<td>TCP + OSI stack</td>
<td>TCP/HTTP/Binary</td>
<td>TCP + HTTPS</td>
</tr>
<tr>
<td>Integrated security</td>
<td>No</td>
<td>Yes</td>
<td>OPC UA</td>
</tr>
<tr>
<td>Discovery mechanism</td>
<td>No</td>
<td>WS-Discovery</td>
<td>UA Discovery</td>
</tr>
<tr>
<td>Session management</td>
<td>No</td>
<td>Yes</td>
<td>UA Session</td>
</tr>
<tr>
<td>Meta-modeling capability</td>
<td>No</td>
<td>OPC UA</td>
<td>AddressSpace</td>
</tr>
<tr>
<td>Data encoding</td>
<td>Binary</td>
<td>XML</td>
<td>XML/Binary</td>
</tr>
<tr>
<td>Event delivery mechanism</td>
<td>Report Service</td>
<td>WS-Eventing</td>
<td>Subscription Service</td>
</tr>
<tr>
<td>Asynchronous</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Available open source stack</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Therefore, the problem of creating device-level SOA middleware for IEC 61850 reduces to finding a specific profile of OPC UA Services which fulfills ACSI service requirements.

The architectural overview of this novel device-level SOA middleware architecture for IEC 61850 applications is presented in Fig. 4. It outlines the relationships between the DPWS protocol stack and OPC UA Services required for ACSI functionalities. The middleware mapping details and distinctive features are described in the following subsections.

5.2. Semantic Smart Grid modeling services

The first step in creating new Smart Grid automation applications is semantic modeling of communicating entities. The proposed IEC 61850 middleware supports OPC UA AddressSpace modeling concepts. This feature facilitates enterprise-level integration of IEC 61850 devices and provides a framework for semantic-enabled applications such as self-manageable microgrids.

Although IEC 61850 defines Server/LD/LN/DO/DS ACSI service models which are dependent on the data structure level, this IEC 61850 functionality can be achieved by using AddressSpace management services which are not influenced by the data hierarchy structure. These OPC UA Services are:

- The NodeManagement Service Set: Services which allow the client to add and delete Nodes and References in the AddressSpace.
- The View Service Set: Services for browsing the AddressSpace or its subsets (Views).
- The Attribute Service Set: Services that allow clients to read and write Attributes of Nodes, including the value attribute.

The described services enable complete AddressSpace manipulation and fulfill all IEC 61850 information modeling requirements. An example of organization of the IEC 61850 data model based on AddressSpace concepts which can be managed by the aforementioned services is described in the following subsection.

5.3. IEC 61850 semantics based on AddressSpace concepts

IEC 61850 information models can be created with the help of OPC UA Services using only a subset of AddressSpace components. The proposed modeling approach divides IEC 61850 data classes into two categories: hierarchy modeling classes and endpoint modeling classes. This approach is also suitable for self-manageable microgrid applications. All IEC 61850 data classes except the DA class, are used for modeling data hierarchy. Hence, these classes are modeled as OPC UA ObjectType connected with HasComponent
Event-driven data exchange is one of the crucial requirements for future self-manageable microgrid applications. Integrating event-driven architecture (EDA) principles enables scalable and flexible application design. Furthermore, it optimizes communication bandwidth usage in distributed systems [30]. In case of IEC 61850 applications, EDA design is based on using RCB ACSI service models. Therefore, they can also be based on the previously described AddressSpace management services.

5.5. Event-driven data exchange

Event-driven data exchange is one of the crucial requirements for future self-manageable microgrid applications. Integrating event-driven architecture (EDA) principles enables scalable and flexible application design. Furthermore, it optimizes communication bandwidth usage in distributed systems [30]. In case of IEC 61850 applications, EDA design is based on using RCB ACSI service models.

5.5.1. IEC 61850 reports

RCB ACSI service models define abstract application-level logic for managing publish/subscribe mechanisms and enabling event-driven data exchange [11]. IEC 61850 reports are new DA values created as a result of IEC 61850 events, together with their related information, are grouped into an IEC 61850 report and sent from the device to the report handler application. IEC 61850 ACSI specifies two RCB class models, referred to as buffered and unbuffered [11]. The buffered RCB (BRCB) class model allows for the buffering of events at the device level and guarantees sequence-of-event functionality in case of connection loss. Conversely, the unbuffered RCB (URCB) class model immediately starts sending reports on a “best effort” basis. The RCB ACSI models involve the following three basic services, where (X)RCB represents both BRCB or URCB:

- Set(X)RCBValues: A service used for managing settings of RCB objects on the server side. These settings enable/disable event-driven data exchange and define the format of IEC 61850 reports.
- Get(X)RCBValues: A service used for retrieving the settings of RCB objects from the server.
- Report: A service supporting spontaneous data delivery.

Implementing these services in the proposed device-level SOA middleware implies merging IEC 61850 reports with the DPWS event notification mechanism and adequate OPC UA Services.

5.5.2. Mapping reports to DPWS and OPC UA

The event-driven notification delivery mechanism for the DPWS platform is defined through WS-Eventing specification. The publish/subscribe paradigm of WS-Eventing involves an Event source (the publisher), a Subscriber, an Event sink and a Subscription manager. WS-Eventing includes several subscription related operations: Subscribe (create subscription), Renew (update subscription expiration), GetStatus (retrieve subscription status), Unsubscribe (explicit deletion of a subscription) and Subscription-End (indication of an unexpected termination of a subscription to an optional entity). The relationship between WS-Eventing entities and their respective operations is depicted in Fig. 6.

The WS-Eventing specification supports only raw, application-neutral messages which do not encapsulate any topical information and can, thus, be easily used as IEC 61850 reports. Message notification is based on a “push” default delivery mode which is completely asynchronous, fulfilling one of the most important microgrid automation requirements.

OPC UA, on the other hand, defines two application-level service sets. The first is the MonitoredItem Service Set which allows OPC UA clients to create, modify, and delete MonitoredItems (i.e., items used to monitor Attributes for value changes). The Subscription Service Set allows OPC UA clients to create, modify and delete Subscriptions (i.e., collections of MonitoredItems which send Notifications to clients in case of value changes). These services sets are fully conformant to RCB ACSI service models. However, in order to adapt them to asynchronous HTTP-based data exchange, they need to be combined with WS-Eventing capabilities. The mapping between their notification concepts is presented in the sequence diagram in Fig. 7.

From a WS-Eventing perspective, the IEC 61850 application is the Event sink. In order to be consistent with RCB ACSI, the Subscriber, Subscription manager and Event source are parts of the IEC 61850 device. This is possible since WS-Eventing allows for
decoupling of the Event sink and the Subscriber. The subscription process on the IEC 61850 application side starts with receiving a Set(X)RCBValues service request. This request is then mapped to the corresponding OPC UA service requests through a consecutive call of the CreateMonitoredItems and CreateSubscription services. The IEC 61850 device then extracts the relevant SOAP message payload used for setting an RCB object and the Subscriber sends a Subscribe request to the Subscription Manager/Event source. WS-Eventing events are formed as OPC UA Notifications which respond to IEC 61850 reports according to requirements of the previous Set(X)RCBValues service request. With the help of WS-Eventing mechanisms, OPC UA Notifications are published directly from the Event source to the Event sink without the need for previous polling. The unsubscribe process follows similar steps as the subscribe process, except that it forms a corresponding DeleteSubscription and DeleteMonitoredItems requests.

The described solution demonstrates a unified approach for OPC UA and WS-Eventing notification. This mapping procedure is compliant with RCB ACSI functional requirements and compatible with the application-logic of existing IEC 61850 equipment. Therefore, the proposed solution can also be conveniently applied as part of a gateway for upgrading legacy IEC 61850 applications and devices.

The Log-Control-Block (LCB) model is used for the retrieval of historical events related to the device. It does so by request and therefore does not require spontaneous event delivery as in RCB ACSI models. The LCB model can use a polling-based OPC UA event retrieval mechanism.

6. Plug-and-play DER integration and simulation of the self-manageable microgrid application

One of the most significant benefits of the proposed middleware platform is its capability of integrating DERs into microgrid applications without human intervention, i.e., plug-and-play integration of DERs. This section provides details regarding DER plug-and-play mechanisms and analyzes features of the proposed middleware platform in a simulation environment consisting of a DC microgrid.

6.1. Plug-and-play integration of semantic-enabled DERs into a self-manageable microgrid

Engineering of common IEC 61850 systems (i.e., substation automation systems) is based on preconfigured communication
entities with relatively static electric network and communication network topologies. This includes static IPv4 addresses for communicating entities and a pre-engineered list of process data signals that are described in XML documents based on the System Configuration description Language (SCL) [31]. Usually, these systems have only single application functionality (e.g., Supervisory Control and Data Acquisition – SCADA). Microgrids, however, are envisioned as constantly changing systems which require dynamic DER integration, handle reconfigurable network topologies and provide several application functionalities (e.g. optimized power production, market-driven control, and enterprise integration capability). Fulfilling these requirements is possible by integrating DER plug-and-play interaction principles into microgrid applications. Plug-and-play principles can be summed up as a group of characteristics which enable the automatic discovery of functionally described interacting entities in order to enable a two-way flow of information. The device-level SOA middleware for IEC 61850 systems proposed in this paper is complementary to these principles and, therefore, provides a feasible semantic-enabled integration framework supporting self-manageable microgrid applications.

6.1. Device discoverability

Device discovery in the proposed middleware platform is an inherent DPWS feature based on WS-Discovery specifications. WS-Discovery defines three different endpoint types: Target services, Clients, and Discovery proxies. In the DPWS domain, a Target service is a Hosting device which provides device functionalities over the network. In the context of IEC 61850, these functionalities are ACSI-based services. Clients are able to dynamically discover Target services (Hosting devices). The Discovery proxy acts as a mediator between Clients and Hosting devices outside local networks.

WS-Discovery specifies four basic operations, denoted as operations Probe, Probe match, Hello and Bye, to discover Hosting devices. For explicit discovery, a Client can send a multicast Probe message in response to which it will receive a Probe match message if a Hosting device exists. For implicit discovery, a Client can listen and wait for Hello and Bye multicast messages sent by Hosting devices used to announce their availability. This functionality allows microgrid applications to dynamically discover IEC 61850-based DERs.

6.1.2. Self-descriptive services

Another important functionality supported by the DPWS protocol stack is the possibility of providing metadata descriptions of available Hosted services using WS-MetadataExchange. Since IEC 61850 systems do not necessarily support the complete set of AC-SIs, this feature enables identification of the services available. In the developed middleware prototype, the metadata format for ACSI-based Hosted services is based on OPC UA WSDL documents found in [10].

6.1.3. Semantic-enabled DERs

Each IEC 61850-based DER provides a set of semantically annotated data. Using the standards-based semantic definition of DER data enables streamlined modeling of expert microgrid applications. The proposed middleware platform enables automatic integration of device capabilities using AddressSpace management services.

6.2. The simulation environment

The semantic model of the simulated self-manageable DC microgrid based on IEC 61850 definitions and relationships among software-in-the-loop simulation components is presented in Fig. 8 and described in Table 2.

The microgrid’s electrical characteristics are simulated using Matlab’s Simulink packet. The proposed device-level SOA middleware prototype is based on combining the DPWS Core Stack [27] and the OPC UA ANSI C stack [8]. The server side component of the proposed middleware communicates through a Matlab C API in order to change simulation parameters and provide on-line simulation results. The client side of the proposed middleware communicates with an IEC 61850-based microgrid management application which uses the simulation results to calculate the optimal set points for each DER. The computers used in the simulation are part of the same 100 Mbit local area network (LAN). Detailed analysis of geographical distribution of DERs in the controlled subsystems which could influence the communication network is out scope of this research. The proof-of-concept application enables integration of new DERs into the microgrid. This is done by analyzing compliance of DER-provided data with standards-based semantics. Furthermore, the data is used to calculate optimal simulation set-points using the microgrid management algorithm and then returning them to the simulation. However, the proposed middleware platform is not bounded to specific Smart Grid subsystem type such as DC microgrid. It can be adapted to any distributed subsystem AC microgrid or VPP which can be described by using IEC 61850 data semantics. A detailed description of the analyzed DC microgrid use case is provided in the following subsection.

6.3. Use case: Automatic integration of a new battery system into the droop-controlled DC microgrid

It is widely agreed that the droop-control method is a viable solution to connect several power sources in parallel [32]. For DC microgrids, this method is based on setting equivalent resistances [33] between particular DER and the microgrid. The equivalent resistances, together with the impedance already existing within the system, influence the power injection/extraction between DERs and the microgrid. To achieve more flexibility, equivalent resistances for battery systems can be made based on various criteria, such as the battery system state-of-charge (SOC), its capacity, whether the battery system is in the process of charging or discharging, etc. In the analyzed use case, there are several requirements for the system behavior. The first one is that battery systems with higher SOC values discharge faster than those with lower ones. The second requirement is that battery systems with lower SOC values charge faster than those with higher ones. Also, in order to keep SOC levels stable, the rate of charge/discharge needs to be linearly proportional to their capacity.

Therefore, to meet these requirements, calculation of the equivalent resistance for battery systems in the microgrid is proposed as:

\[ C_{\text{max}} = \max(C_i) \]  

\[ R_{\text{charge}} = \frac{C_i}{C_{\text{max}}} \cdot (100 - \text{SOC}_i) \]  

\[ R_{\text{discharge}} = \frac{C_i}{C_{\text{max}}} \cdot \text{SOC}_i \]  

In (1)–(3), \( C_i \) represents the nominal capacity of each battery system and \( C_{\text{max}} \) represents the nominal capacity of the battery system with the highest value of nominal capacity among all battery systems within the microgrid. Calculation of the equivalent resistance (\( R_i \)) depends on whether the battery system is charging (\( R_{\text{charge}} \)) or discharging (\( R_{\text{discharge}} \)).

The capability of real-time changes to equivalent resistances can be further exploited by matching the system’s worst-case
response in a predicted manner. Eqs. (4)–(6) describe the static behavior of a droop-controlled DC system. (4) is used for calculating the voltage deviation ($D_{V}$) according to the reference DC voltage ($V_{ref}$) and the measured DC voltage ($V_{DC}$).

The boundary on the maximum voltage deviation in the analyzed use case was set to 1.5 V.

The DER device current ($I_{DER}$) is expressed as a relationship between $D_{V}$ and the equivalent resistances of all the DERs in the microgrid (5). The new extraction power for each device ($P_{i}$) also depends on several already defined criteria as shown in (6). An additional requirement, given in (7), limits $P_{i}$ according to the specific DER capabilities. Semantic descriptions of the variables used in Eqs. (1)–(7) provided by simulated IEC 61850 DER controllers are described in Table 2.

$$\Delta V = V_{ref} - V_{DC}$$  \hspace{1cm} (4)

$$I_{DER} = \frac{\Delta V}{\sum_{i=1}^{n} R_{i}}$$  \hspace{1cm} (5)

$$P_{i} = I_{DER} \cdot V_{DC} \cdot \left( \sum_{j=1}^{n} \frac{R_{j}}{R_{k}} \right)$$  \hspace{1cm} (6)

$$P_{i} \leq P_{i}^{max}$$  \hspace{1cm} (7)

It can be easily noticed that both the DC microgrid voltage and the power of a particular source can be explicitly calculated, providing that all the equivalent resistances and the voltage deviation are known. By taking into account the highest expected load that can occur in the system and the available values of the equivalent resistances, the maximum deviation of the DC voltage from its nominal value is always available. In the analyzed use case, the worst case load was set to 1250 W. With a fixed worst-case load, the maximum deviation can be influenced by changing the equivalent resistances. An efficient way to do this is by multiplying (2) and (3) with some non-dimensional parameter since the programmed sharing relationship between DERs will not be affected.
By using the proposed middleware platform and IEC 61850 data semantics, this can be done automatically in real-time and without human intervention.

The trade-off between the nominal voltage deviation and the quality of the transient response is tuned according to the following principle: in the worst case, a system is operated at the deviation margin so that the equivalent resistances are kept at their most efficient value with respect to the transient response [34].

According to the definitions provided in the previous paragraphs, a use case illustrating the scenario of adding a new battery system to the microgrid using the proposed middleware platform has been simulated and analyzed.

Fig. 9 represents a sequence diagram of service calls required for completing automatic integration of DERs based on plug-and-play principles. After connecting a new battery system to the microgrid, the first step is its discovery by the microgrid application. After discovering the DER device, the microgrid application retrieves data about supported ACSI-based Hosted services. In the presented use case, the simulated battery system controller supports all vertical ACSI services. Then, the microgrid application
enables a session with the DER and retrieves the OPC UA-based device information model that is compliant to IEC 61850 definitions. Standards-based semantics of available process information enable semantic integration of the data required for self-manageable microgrid applications. A detailed description of the data semantics is given in Table 2. Depending on the functional goals, the microgrid application subscribes to a specific subset of relevant data which is required for process control. In the analyzed use case, this is the data needed to calculate the optimal equivalent resistances. After calculation, the equivalent resistances are sent back to the device as new operational settings. This step completes the semantic-enabled plug-and-play process. More detailed descriptions of the services used in Fig. 9 is out of scope of this paper and can be found in [7,8].

Fig. 10 shows the characteristics of the DC voltage and load current in the microgrid according to the system events related to integrating a new battery system and increasing the power consumption in the worst case scenario. For the same period as in Figs. 10 and 11 shows the changes in the values of the equivalent resistances of the battery systems in the simulated microgrid, as well as their initial simulation parameters. These results show that the proposed middleware platform is suitable for developing expert microgrid applications and is a feasible solution for device-level SOA mapping for IEC 61850 systems.

6.4. Future work

The proposed middleware platform is based on the OPC UA device model and, therefore, provides the capability of automatically integrating DER devices with a diverse set of automation and enterprise-level OPC UA-compliant applications. Our future work will be based on analyzing the integration capabilities of the proposed middleware platform with Distribution Management System (DMS) applications commonly used in control centers, such as market-based and power system optimization applications which utilize Common Information Model (CIM) [35]. Together with applications based on CIM, the proposed middleware will provide a unified semantic-based and service-oriented integration framework for the Smart Grid.

7. Conclusions

Standards-compliant and vendor-independent communication is one of the key prerequisites for seamless Smart Grid integration. Industrial standard IEC 61850 is a globally accepted solution and
one of the prime movers of flexible and adaptable Smart Grid development. Although primarily defined for substation domain, the IEC 61850 architecture is being extended for other Smart Grid entities such as DERs, electric vehicle supply stations and smart houses/buildings. Nonetheless, certain parts of the current IEC 61850 definition cannot cope with requirements of next-generation Smart Grid applications and control models, such as self-manageable DC microgrids. In order to provide a technically viable solution, this paper provides several original contributions as follows:

- **IEC 61850 architecture requirements are analyzed in the context of a semantic-enabled and service-oriented Smart Grid integration framework.** As a potential solution, a standards-based SOA-compliant application design for next-generation IEC 61850 systems is proposed.

- **A multi-criteria comparative analysis of state-of-the-art device-level SOA middleware technologies is performed according to IEC 61850 vertical communication requirements in order to distinguish the key features applicable to Smart Grid applications.**

- **A novel standards-based middleware approach based on combining DPWS and OPC UA features is proposed to complement vertical ACSI service models for use in self-manageable Smart Grid applications.**

- **It is shown that the proposed middleware provides important value-added features for microgrid management such as discoverability and self-descriptiveness of field devices.**

- **Device plug-and-play integration capability provided by the proposed middleware platform is demonstrated and analyzed in a simulation environment with a self-manageable droop-controlled DC microgrid.**

- **A new method for selecting the optimal values for equivalent resistances for DERs in droop-controlled microgrids has been developed and evaluated in the simulation framework.** Furthermore, the features enabled by the proposed middleware mapping of vertical communications in IEC 61850 systems carry with them some additional advantages. First, they enable shorter time-to-market Smart Grid device development resulting from the availability of open source implementations of the used middleware stacks. Second, they imply a decrease in system integration time-frames (enabled by the plug-and-play capability) and, thus, allow for more accelerated microgrid deployment.

The middleware mapping presented in the paper demonstrates extensibility of IEC 61850 systems and provides proof-of-concept for plug-and-play DER systems which could accelerate Smart Grid architecture adoption. However, applying the proposed integration principles to the real world power systems can imply additional requirements such as regulation policy and hence add to the complexity of the proposed system.

**References**


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