SGAM-based methodology to analyze Smart Grid solutions

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Abstract— The design of future energy automation and management systems requires Distribution System Operators (DSOs) to analyze and compare different technical solutions for determining which of these could be best implemented in their networks. This paper presents a methodology that helps DSOs carry out such a complex task. The methodology is based on the Smart Grid Architecture Model (SGAM) framework. It was implemented using a web-based application that facilitates editing and automatic analysis of SGAM architectures. The methodology was successfully evaluated in context of a large European project.

Keywords: Distribution System Operator, Smart Grid architectures, SGAM, Use Case

I. INTRODUCTION

The Smart Grid vision has led to new demands on electric distribution systems. For example, the distribution networks should be able to integrate Distributed Energy Resources (DER), Electric Vehicles (EV), or Demand Response systems (DR), while guaranteeing the quality of supply to customers at a cost effective price [1]. To address these demands, numerous solutions have been proposed, such as: distributed systems for automatic fault detection and power restoration [2], advanced metering infrastructures [3], or semantically enabled automation and management systems [4]-[6]. Furthermore, there is also an increased effort to promote standardization that would assist adoption and flexibility of such solutions [7]-[9].

Distribution System Operators (DSOs), therefore, have an increasing need to analyze these solutions and standards and decide which ones should be used in their automation and management systems to meet the Smart Grid requirements, while optimizing the investments.

This article presents a methodology that helps DSOs to perform this rather complex task. The methodology makes it easier for users to decide which new solutions and standards should be implemented in their systems by facilitating assessment of different Smart Grid system architectures. The methodology is based on the Smart Grid Architecture Model (SGAM), which is a reference framework defined by EU Mandate M/490’s Reference Architecture working group for representing Smart Grid architectures [10]. Until recently, the SGAM has been used mainly by standardization bodies to identify standardization gaps [11]. In this paper, the SGAM has been enhanced for enabling DSOs to analyze Smart Grid architectures, taking into account their business objectives as well as economic and regulatory constraints.

The methodology was evaluated in context of the DISCERN project [1]. DISCERN is a large European project in which five DSOs exchange knowledge on Smart Grid solutions developed in previous research projects.

This paper is organized as follows: Section II presents the background related to the proposed methodology. The proposed SGAM based methodology is then presented in Section III. Section IV briefly describes the web-based application developed in this work as tool support for the methodology. Section V focuses on the evaluation of the methodology in DISCERN. Finally, Section VI concludes the paper and provides an outlook on future work.

II. BACKGROUND

The methodology proposed in this work relies on the SGAM framework, which is closely related to the Use Case approach defined in the IEC 62559 standard [12]. This section gives an overview on these two foundations: Use Case approach and SGAM framework.

A. Use Case Approach – IEC 62559

Use cases, originating from the Software-Engineering discipline, describe a particular goal that an actor or a set of actors want to achieve with a system of interest. These actors can be humans, organizational entities, components or external systems [9].

How the actors achieve this goal is described within the use case in several scenarios. Each scenario details a sequence of steps in which the involved actors exchange information with each other. The information exchanges detailed in a use case define the functional requirements of the system under design. In addition, steps can be associated to non-functional requirements, such as configuration issues, data management issues, quality of service issues, or security issues.

However, there is no uniform definition about what a use case is, the scope of systems to be described, or the information used to describe a use case. In this regard, several notations and templates exist, Unified Modelling Language
(UML) being the most prominent one for the graphical notation of use cases.

In the context of energy systems, a use case template and a related development method are provided with the IEC 62559-2 standard [13]. With this five-phase methodology, use cases are developed incrementally, by domain experts (e.g. distribution system engineers, operators) at first and enhanced with technical information and communication technology (ICT) details provided by ICT experts later on. These sets of activities should finally lead to a technical requirements specification for implementation. This approach, originally stemming from the US EPRI IntelliGrid program [14], has been taken up again in the standardization work of the EU Mandate M/490 working group on “Sustainable Processes” to support the identification of standardization needs [15]. The use cases served in this EU initiative as the basis for the description of Smart Grid functionalities and were harmonized to develop a common understanding. This resulted for example in an identification and proposal of common “power system actors” [11], [16] which improve reusability of use cases among different companies. In the same way, the IntelliGrid program proposed a list of non-functional requirement types [14]. This list could be used in power system related use cases to facilitate agreement on common semantics and level of detail on the non-functional requirements.

B. Smart Grid Architecture Model (SGAM)

The Smart Grid Architecture Model (SGAM) is a key outcome of the EU Mandate M/490’s Reference Architecture working group [10]. It provides a structured approach for developing Smart Grid architectures.

In addition to providing an intuitive high-level framework for representing Smart Grid solutions, the SGAM enables to identify interoperability issues in system under design. Thus, available standards and standardization gaps for each solution can be easily represented in this framework. Furthermore, the SGAM allows establishing clear relationships between: 1) the business objectives that explain the benefits derived by the company with the solution, 2) the technical functions that are required to realize such solution, 3) the information exchanges between the functions, 4) the standard protocols and data models that enable these information exchanges, and 5) the components that implement the technical functions in the system. Finally, it is worth noting that in use cases it is possible to define which actors are involved in a system, but it is not possible to represent how these actors are implemented in the physical distribution of the system. The SGAM framework enables users to do this.

A central element of the SGAM is its five-layered, cube-like visualization (Fig. 1). The SGAM’s structure is described more detailed below.

1) The SGAM Smart Grid Planes: A Smart Grid plane is the basic viewpoint of a resulting SGAM architecture visualization. Each plane is structured by the domains of the energy conversion chain on the one side, and with the hierarchical zones of power system management on the other side. The energy conversion chain includes the following domains: Generation, Transmission, Distribution, Distributed Energy Resources (DER) and Customer Premises.

The hierarchical zones of power system management are: Process (physical, chemical, or spatial transformations of energy and the physical equipment directly involved), Field (equipment to protect, control, and monitor the process of the power system), Station (areal aggregation level for field level), Operation (power system control operation in the respective domain), Enterprise (commercial and organizational processes, services and infrastructures for enterprises), and Market (market operations possible along the energy conversion chain). The planes can be used to depict different architectural aspects.

2) Interoperability Layers: Interoperability is an essential requirement for systems and components interacting in Smart Grids [15]. The Grid Wise Architecture Council (GWAC) developed a model that represents the organizational, information specific and technical aspects in eight categories [16]. In order to create interoperable systems, each of these categories must be addressed during development. These eight categories were mapped onto five interoperability layers in the SGAM, i.e. the visualization contains five Smart Grid planes, each of which addresses certain interoperability issues. These five interoperability layers in the SGAM are: Business, Function, Information, Communication, and Component (see Fig. 1). The business layer includes business-specific aspects of information exchange in Smart Grids, such as business objectives and processes, organizational entities, and regulatory conditions. The function layer describes logical functions and services as well as the relations among from a technical perspective to realize respective business aspects. The information layer represents the information being exchanged between these functions, realized by certain systems. The descriptions adhere to data models and derived information objects. The communication layer consists of protocols and mechanisms for exchanging those objects specified in the information layer. Finally, the component layer comprises physical components, like grid equipment, devices, and software applications, which allocate the functions and communicate among themselves using the specified information objects and communication protocols.

Fig. 1. SGAM framework
III. METHODOLOGY

The methodology proposed in this work is aimed at helping DSOs decide which new solutions should be implemented in their systems. The methodology comprises two steps: Creating SGAM architectures and Analyzing SGAM architectures (Fig. 2).

A. Creating SGAM architectures

As stated previously, there are numerous solutions in the state of the art to address Smart Grid demands, as well as several standards promoting interoperability in Smart Grid systems. The first step of the methodology refers to the representation of the solutions under study (along with recommended standards) in SGAM. In that way, the solutions will be described in a common framework, enabling their comparison and analysis.

Typically, SGAM architectures are developed from use cases [10]. To ensure consistency in the SGAM architectures and also in the corresponding use cases, it is necessary to agree on common lists of actors that can be involved in a domain. Section II-A explain that the state of the art proposes lists of actors for the electric power system domain [11], [16]. However, existing lists are usually large glossaries of terms without any structure. It is, therefore, very difficult to differentiate between overlapping terms within the glossaries, thus hindering the task of finding the term that better fits with each actor. For this reason, a taxonomy of actors has been developed in our work.

The taxonomy is based on existing glossaries [11], [16] and on international standards in the electricity sector, mainly the IEC 61968-1 [17] and the IEC 61850-5 [18]. It organizes the terms hierarchically, making it easier for users to find their use case actors. Further, it establishes formal relationships between the terms, avoiding semantic overlapping. Lastly, it should be noted that the hierarchical organization of the taxonomy facilitates the extension of the common library of actors. This makes it possible to reuse this library in different applications within a domain, enabling the exchange and comparison of different Smart Grid architectures used in projects.

![Fig. 3. Extract of the “actor taxonomy”](image)

Fig. 3 shows an extract of the proposed “actor taxonomy”. As can be seen, two types of actor derive from the root term: BusinessLayerActor and ComponentLayerActor. The first one refers to the actors that must be represented in the business layer; that is, persons, organizations, or roles. The second one refers to the actors that must be represented at the component layer in SGAM; that is, grid equipment, devices, or software applications.

In addition to the actor taxonomy, two additional taxonomies were created in this work defining the types of scenarios and types of requirements, respectively, that should be used in the electric power system domain. It is worth stressing that, using the approach of the EU Mandate M/490’s Reference Architecture working group in [10], we are considering that use case scenarios describe sequences of steps required to realize technical functions. In that way, the scenario types refer to the technical functions that should be performed by the systems that control and manage the electric networks. The “scenario taxonomy” developed in this work relies on the Interface Reference Model (IRM) of the standard IEC 61968-1, because this model defines the technical functions that should be carried out in distribution management systems. Meanwhile, the “requirement taxonomy” is based on the non-functional requirements proposed in [14].

Once the use cases have been created (by using the taxonomies mentioned above), the methodology proposes to map them into the SGAM framework, by following the stepwise process defined in [10] and, in further detail, in [18].
B. Analyzing SGAM architectures

The second step of the methodology deals with the analysis of SGAM architectures. This analysis helps DSOs identify the solutions that should be used in their systems. It also allows defining the requirements of the new components that should be installed in the systems in order to implement the new solution or functionality (Fig. 4).

Next, the process that should be followed to analyze SGAM architectures is described. First, the DSO studies the business layer of the SGAM architectures and identifies which of these architectures address its business needs. For instance, let us suppose that the DSO is interested in the solutions whose objective is “to improve network observability”. In that case, the DSO chooses the SGAM architectures that include that objective in the business layer.

Once the SGAM architectures that will be further analyzed have been identified, the DSO finds in the function layer which technical functions must be added in its systems to implement the new solution. For example, let us suppose that one of the architectures chosen by the DSO includes the function “Sequences and Imbalances” and that the current systems do not include any component with the ability of detecting sequences and imbalances in the network.

From the new functions identified, the DSO finds in the component layer which new components (devices or software applications) are needed to implement these functions. Following with the example, let us suppose that the function “Sequences and Imbalances” is realized by an Intelligent Electronic Device (IED) placed in the field zone.

Finally, for each new component, the DSO analyzes in the communication and information layers which information these components must exchange (functional requirements) and which communication standards are recommended to enable these information exchanges. Moreover, the DSO can find in the use case which are the non-functional requirements associated with these new components. For instance, let us suppose that the IED of the example must receive voltage and current measurements from the grid and send information about harmonics and imbalances to a data aggregator. Further, let us suppose that the recommended standard for enabling these information exchanges is the IEC 61850 and that the device must meet some additional requirements in terms of quality of service, such as “elapsed time response of 1-4 milliseconds”.

In that way, this step-wise analysis of the SGAM architectures enables DSOs to identify which are the requirements of the new components that must be added to their systems, in order to implement a new functionality that will help DSOs achieve their business needs.

IV. IMPLEMENTATION

With the aim of providing tool support to the methodology defined in Section III, a web-based Use Case Management Repository (UCMR) was developed in this work.

Processing SGAM architectures in software applications enables to automatically extract relevant information from several solutions. Nevertheless, due to the lack of semantics in the SGAM framework, until know the SGAM planes are just drawings, which can be easily interpreted by humans, but not by applications that perform automatic analyses from the architectures. Section IV-A briefly describes the XML Schemas developed in this work to solve this problem. The schemas enable to exchange use cases and SGAM architectures between different applications and were created from a data model that formally relates SGAM concepts and use case concepts.

A. XML Schemas

The standard IEC 62559-3 [20] defines a data model relating use case concepts, such as: actors, scenarios, steps, requirements, etc. Moreover, the standard includes an XML Schema derived from that model. The IEC 62559-3 XML Schema aims at facilitating exchange of use case repositories.

In our work, the IEC 62559-3 data model has been extended by adding the relationships of use case concepts and SGAM concepts, such as: components, technical functions, information models, protocols, etc. This extension is based on the meta-model proposed by Dänekas et al. in [21].

From the extended data model, different XML Schemas were created by following the profiling approach showed in Fig. 5. Each schema describes a different interface: UseCaseRepository.xsd is an extension of the IEC 62559-3 XML Schema for exchanging complete repositories; UseCase.xsd enables the exchange of a single use case; SGAM.xsd enables to exchange a single SGAM model; and finally, ActorLibrary.xsd, ScenarioLibrary.xsd, and RequirementLibrary.xsd enable to exchange libraries of actors, scenario types, and requirement types, respectively. Unlike the original XML Schema of the IEC 62559-3 standard, these XML Schemas include associations by reference (by using xs:key and xs: keyValue terms [22]) to represent relationships that exist in the data model but cannot be represented directly in the hierarchy of the XML Schema. For instance, the XML Schemas developed in this work added associations by reference between the elements Actor and...
InformationProducer within a use case. This relationship establishes that all InformationProducer must refer to an existing actor within the use case. In the same way, associations by reference were established between SGAM components and use case actors, and between SGAM functions and use case scenarios. These new associations by reference can be used to automatically detect inconsistencies within a use case or between a use case and a SGAM architecture by validating an XML file against the corresponding XML Schema. Hence, if a use case described in an XML file includes an InformationProducer that is not named as any actor within the use case, the validation of the XML file against the UseCase.xsd schema will generate a warning detailing such an inconsistency.

B. Use Case Management Repository (UCMR)

The UCMR developed in this work can help users carry out the two steps of the methodology defined in Section III. On the one hand, the UCMR includes a web front-end allowing collaborative editing of use cases and SGAM architectures among different experts within a company, or even from different companies. On the other hand, the UCMR performs automatic analyses from SGAM architectures to extract relevant information for users.

Fig. 6 shows the functional design of the UCMR presented in this work. As can be seen, the features of the UCMR can be categorized in three groups: Importing use cases and SGAM architectures, Management of use cases and SGAM architectures and Analyzing use cases and SGAM architectures.

1) Importing use cases and SGAM architectures. It is possible that some use cases and SGAM architectures have been already developed in different formats. For instance, the use cases might have been produced in MS Word files based on the use case template defined in IEC 62559-2 standard [11]. In the same way, there might be SGAM architectures represented in well-known generic applications, such as MS Visio. Lastly, it is also possible that the use cases and SGAM models have been produced in UML tools, such as the Enterprise Architect (EA) tool box developed in the IntegrA project [23], [24]. The objective of this functional category is to represent and store all these external use cases and SGAM architectures developed in different tools into a common format. This will facilitate the management and automatic analysis of these descriptions. The common format used in the UCMR is given by the XML Schemas described in Section IV-A. Therefore, the UCMR developed in this work relies on data models that extend the standard IEC 62559-3.

2) Management of use cases and SGAM architectures. This functional category comprises: editing of imported use cases and SGAM models, definition of new entities (such as, actors, functions, or components), and creation of new use cases and SGAM models. These tasks can be carried out in collaborative works by means of the web front-end of the UCMR.

3) Analyzing use cases and SGAM architectures. In addition to providing a common repository for use cases and SGAM architectures, the UCMR also enables the automatic analysis to extract relevant data from these descriptions. The analyses performed by the UCMR are: comparison of SGAM architectures, extraction of requirements for new components, and 3-D visualization of SGAM architectures. The comparison of SGAM architectures uses simple parameters, such as number of common components, functions or information objects.
V. Evaluation

The methodology proposed in this work was evaluated in the context of a large European project called DISCERN [10]. One of the objectives of this project is to facilitate knowledge sharing among 5 DSOs. Section V-A provides an overview of DISCERN. Section V-B describes the approach followed in the project to enable knowledge sharing among the DSOs. Finally, Section V-C explains how the methodology presented in this paper was used in DISCERN.

A. DISCERN project

The aim of the DISCERN project is to assess the optimal level of intelligence in the distribution network and to determine the replicable technological options that will allow a cost-effective and reliable enhancement of observability and controllability of the future distribution networks in Europe. DISCERN builds on five demonstration projects operated by major European DSOs allowing to gain required insight and evaluate the results (Fig. 7). These projects unite a variety of technological approaches addressing different challenges, briefly presented in the following text:

• The Smart Grid Gotland project (lead by Vattenfall) focuses on the medium voltage level on the Swedish island Gotland, where a very high share of wind power is available occasionally exceeding the local demand of approximately 40,000 customers.

• New Thames Valley Vision (SSE) addresses the low voltage level and deals with the increasing share of DER and the increasing overall demand of 30,000 customers in Bracknell, UK.

• PRICE (Iberdrola and Union Fenosa distribución) is concerned with the increasing share of DER that affects the power quality, in the medium and low voltage levels, involving 200,000 customers in the Madrid area in Spain.

• ANA—Autonomous low voltage agents (RWE) takes place in the German city Augsburg, where a high share of DER, photovoltaic in particular, is connected to the low voltage grid. The project involves 2–3 low voltage networks including 150 households per network.

• Future Networks (RWE) deals with a very high share of DER in the medium voltage level, where the supply exceeds the demand. The project is carried out in Bitburg, Germany and involves 3,000 households.

B. Leading, Learning, Listening approach

One aim of DISCERN is to enable a common understanding among the projects and to enable the exchange of experiences regarding technological options for the realization of Smart Grid systems developed in these projects. For this purpose, the first step of DISCERN was to align the projects to “Smart Grid functionalities” highlighted by European Commission Task Force for Smart Grids [25]. This alignment resulted in a refined and more specific subset of sub-functionalities to be examined in DISCERN as demonstration and simulation projects [26].

In order to facilitate the efficient exchange of information and provide a consistent means to define a DSOs contribution level to knowledge exchange, the concept of Leading, Learning and Listening DSO was introduced in the project. These roles have been defined for the DSOs in each DISCERN sub-functionality.

Leaders are the DSOs with good knowledge on the sub-functionality, because they have implemented it in previous research projects. The DSO is leading by providing input to other DISCERN partner DSOs who are considering to implement this functionality and also making it available to a comparative assessment within DISCERN.

Learners are the DSOs that will learn from the information provided by leaders in order to implement this sub-functionality in their own networks during the project. This means the DSOs that bring forward their demonstration sites for learning are interpreted as evaluating new solutions through simulations and pilot installations.

Listeners are the DSOs that will study the information provided by leaders and learners with the aim of performing a feasibility analysis to decide whether it is interesting (and possible) for them to implement the sub-functionality in the future or not. The listener DSOs will evaluate the solution considering their local factors such as grid regulations, climate situation and technology spread.

Figure 8 illustrates a scenario of such knowledge sharing process where a leading DSO brings its past experience of implanting a Smart Grid function, Enhanced Monitoring of MV/LV Network in this case, to the project and shares this knowledge with the learning and listening DSOs. The learner DSO utilizes this knowledge and re-implements the solution in its own network during the project. The listening DSO evaluates both the leading and learning solutions for a possible future implementation in its network.
C. SGAM-based methodology in DISCERN

The SGAM-based methodology presented in Section III enabled the knowledge sharing among the 5 DSOs in DISCERN project. Hence, all DSOs produced the use cases and SGAM architectures for the solutions defined in their corresponding projects. These SGAM architectures were analyzed by the other DSOs. As a result of this process, 3 DSOs (Learners) identified existing solutions in other networks that they will implement in their systems during DISCERN.

Furthermore, the methodology helped learning DSOs analyze Learners’ SGAM architectures and perform the requirement analysis in order to adapt these solutions in their own networks.

VI. CONCLUSION AND FUTURE WORK

This paper presented a novel methodology that helps DSOs identify which new technical solutions could be implemented in their systems in order to meet their business needs. Moreover, the methodology enables the identification of key requirements for new components that would be added to current systems for implementing a new solution.

The methodology is based on the use case approach defined in the IEC TC8 62559 standard series and the SGAM framework developed by the European Union Mandate M/490’s Reference Architecture working group.

With the aim of improving consistency of use cases and SGAM architectures in the electric power system domain, this work developed IEC 61968-based taxonomies of actors and technical functions. Unlike existing glossaries of actors in the state of the art, these taxonomies organize the terms in a hierarchical way, making it easier for users to find the right terms for their use cases or SGAM architectures, and facilitating the extension of these common libraries.

The methodology was implemented in this work through a web-based application (the UCMR) that facilitates the production and analysis of SGAM architectures. The UCMR enables the 3-D visualization of SGAM architectures, the comparison of different architectures, and the extraction of requirements associated with a particular component. Further, it allows for integration of the SGAM architectures into the tool chain of a company by means of interfaces based on XML Schemas that extend the IEC 62559-3 standard.

Finally, the proposed methodology is validated by using it in a large European project where several DSOs have used it to compare and evaluate technical solutions to be used in demonstration projects.

In future work, the UCMR should be able to perform additional analyses, such as: automatic mapping of SGAM architectures to NISTIR 7628 model [27] to infer high-level IT-security recommendations, and integration of Key Performance Indicators (KPIs) in the SGAM architectures to carry out comparisons of technical solutions focusing on their performance or ability to meet predefined objectives. Additionally, this work can be also useful in the standardization bodies. Thus, at present, the identification of standardization gaps is performed manually by using SGAM drawings of numerous Smart Grid solutions. The tool support developed in this work could be enhanced to automate this process.

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