Large-Scale Smart Grids as System of Systems

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ABSTRACT

Smart Grids are advanced power networks that introduce intelligent management, control, and operation systems to address the new challenges generated by the growing energy demand and the appearance of renewal energies. In the literature, Smart Grids are presented as an exemplar SoS: systems composed of large heterogeneous and independent systems that leverage emergent behavior from their interaction. Smart Grids are currently scaling up the electricity service to millions of customers. These Smart Grids are known as Large-Scale Smart Grids. From the experience in several projects about Large-Scale Smart Grids, this paper defines Large-Scale Smart Grids as a SoS that integrate a set of SoS and conceptualizes the properties of this SoS. In addition, the paper defines the architectural framework for deploying the software architectures of Large-Scale Smart Grid SoS.

1. INTRODUCTION

Systems of Systems (SoS) are usually conceptualized as a kind of systems which are built from components which are large scale systems in their own right but that leverage an emergent behavior [1]. As Jamshidi defines [2], SoS is a system consisting of an integration of other independent non-homogeneous systems with a unified goal. In fact, a SoS is usually composed of independent and complex systems geographically extended, whose interaction generates emergent and changing behaviors [1]. Therefore, SoS require to smoothly integrate all the systems that are composed of in order to provide a common behavior driven by a decision support. This integration requires the connection of the systems through the components that constitutes the SoS. These components are characterized because they crosscut organizational boundaries and require flexible mechanisms for allowing interoperability. Several works present as common examples of SoS: air defense networks, power smart grids, intelligent transport systems, smart cities, etc. [1][3][4][5][6][7].

Smart Grids are one of the exemplars of SoS. Smart Grids have emerged as a solution for dealing with the growing energy demand and the expensive energy distribution and generation. Smart Grids promote the integration of traditional and renewable energy resources in distributed, open, and self-managed way. In fact, Smart Grids mean a shift from current centralized energy infrastructures towards more distributed ones [8], and they aim innovative models for energy infrastructure and management to cope with the integration of alternative energy resources and the growing energy demand [9]. Smart Grids are composed of a broad range of energy resources, from large generating systems (e.g., nuclear power plants, or hydro power plants) to smaller generating systems (e.g., small solar farms, or wind generators), all of them operating as a single system providing both power and heat [10][11].

Initially, Lasseter [13] framed Smart Grids as a set of *microgrids* that are connected to the main grid, i.e., small-scale grids that are designed to provide electrical and/or thermal energy for local loads and communities. But currently, it is possible to also speak about Large-Scale Smart Grids that scale up the electricity service to millions of customers [14][15].

One of the main challenges of engineering SoS in general, and Smart Grids in particular, is the design of their architectural components and interfaces as well as to guarantee the interoperability among components at the different layers of the architecture through the specification of communication standards [3]. In this regard, we present in this paper our experience in the Smart Grid domain obtained participating in the large national project ENERGOS (Technologies for the Automated and Smart Management of the Future Distributed Power Networks [16]), and two ITEA projects: NEMO & CODED (NEtworked MOnitoring and COntrol, Diagnostic for Electrical Distribution[17]) and IMPONET (Intelligent Monitoring of Power NETworks [18]).

From this experience in Large-Scale Smart Grids, this paper defines Large-Scale Smart Grids as SoS that integrates a set of SoS. In addition, we present an architectural framework for Large-Scale Smart Grid SoS. In addition, we define the software architecture infrastructure and the technologies and communication standards that should be used to guarantee both data and services interoperability.

The structure of the paper is as follows: Section 2 presents an overview of SoS. Section 3 details the conceptualization of Large-Scale Smart Grids as a SoS and the definition of an architectural framework for deploying Large-Scale Smart Grids Architectures. Finally, conclusions and further work are presented in Section 4.

2. SoS BACKGROUND

SoS are distinguished from large monolithic systems by the five main criteria defined by Maier [1]. These five criteria are: (i) *Operational independence* of elements: The systems of a SoS are independent and useful in their own right; (ii) *Managerial independence* of elements: The component systems are separately acquired and integrated but maintain its management independent of the SoS; (iii) *Evolutionary development*: A SoS is continuously being developed by evolving it following the current needs and purposes; (iv) *Emergent behavior*: Behavior derived from the integration of the systems and whose performance cannot be localized to any particular system; and (v) *Geographic distribution*: Component systems are largely geographically extended in such a way their interaction is mainly limited to information exchange. In addition to these five criteria, DeLaurentis in [20] adds three more criteria to characterize them by defining them as inter-disciplinary, heterogeneous, and network of systems.

Based on these criteria, there also exist classifications of SoS. These classifications define different kinds of SoS depending on factors, such as domain or context, the technology, or the conceptual frame. The classification of SoS based on the management criterion is widely-extended [1][21]. This classification establishes four kinds of SoS: directed, collaborative acknowledge, and virtual. *Directed* SoS are those in which their systems operate subordinated to the central managed purpose. *Collaborative* SoS are those that systems voluntarily collaborate to fulfill the agreed central purposes. *Acknowledge* SoS are those in which there are recognized objectives, a designated manager, and resources for the SoS, and changes in the systems are agreed on collaboration between the SoS and the systems. Finally, *Virtual* systems lack a central management authority and a centrally agreed purpose for the SoS.

Regardless the kind of SoS, one of the challenges of SoS engineering (SoSE) is the architecture design [3]. These architectures should be open, loosely coupled, welcome to changes, and guarantee the interoperability of the different systems and components that are composed of [21]. Maier sets out that the architecture of the SoS should define stable intermediate forms and the usage of standards for the communication among components [1]. These are critical issues because the suitable behavior of the SoS and the achievement of their goals depends on communication process. Therefore, Maier also defines a reference model for communications that consists of five layers [1]: *Application, Upper* (it can be decomposed into more layers), *Transport, Network, and Physical.*

Currently, SoS literature and practical experiences in different SoS claim the fact that system integration will be a matter of necessity and not a choice [3][4]. In addition, Jamshidi adds that future energy will be best managed by using SoS [3].

3. LARGE-SCALE SMART GRIDS AS A SoS

Power networks are undergoing continuous change due largely to (i) the increment in power consumption and (ii) the integration of distributed renewal energy resources. Hence, renewal energy generation—usually based on wind or solar—is inherent variable and weather-dependent being necessary a balance between supply and demand [23]. These changes require the evolution of power networks towards new models and software architectures that enable two-way exchange of power and information between suppliers and consumers (or *prosumers*) based on the introduction of intelligent communication, monitoring, control, and management systems [23]. Smart Grids as SoS have emerged as a new model to deal with these challenge through the *Emergent Behavior* that they leverage.

In Large-Scale Smart Grids, many of these resources, whose interconnection constitutes the Smart Grid (see Fig. 1), are systems, such as solar farms, power plants, hospitals, wind farms, animal farms, industries, the swarm of electric vehicles, smart homes, etc. Most of these systems are categorized in the literature as SoS [3][6]. These *SoS of Large-Scale Smart Grids* have their own management goals and business purposes, sometimes not only related to power decisions. Therefore, they work on their own, but they have an agreement, usually with the utility, in terms of power decisions. This management defines the SoS of Large-Scale Smart Grids as an *Acknowledge* SoS that integrates other SoS, which have *operational and managerial independence.*

Fig. 1. Interconnection of systems in a Large-Scale Smart Grid[1]

A key aspect of Smart Grids is their *open* nature: different kinds of energy generating systems can be dynamically aggregated/removed to/from the power grid. This means that the Smart Grid infrastructure should be *flexible*, to support the connection and disconnection of energy resources to the power grid, and *scalable*, to support the increase in the number of energy resources. These flexibility and scalability requirements that the open aspect of smart grids imposes are very challenging, since they increase the difficulty of controlling and coordinating the range of different elements and the interactions among them. These requirements characterize Smart Grids as *Evolutionary* SoS. Another key aspect of the Smart Grids is the *decentralization* of energy distribution grid services: the energy generation, storage, and consumption should be realized as near as possible to the physical location of consumption/generation in order to achieve greater efficiency of the system [10]. This requires a shift from current centralized energy infrastructures towards more *distributed* ones. In this way, Smart Grids fulfil the fifth criteria of SoS, the *Geographic Distribution.*

Finally, it is important to mention that Smart Grids are also characterized by another two key issues: real time capabilities and interoperability. With regard to real time capabilities, electric companies are demanding solutions that help them manage real time problems in a more efficient and safer way, facilitating, at the same time, the integration of real time information on all corporate applications. Smart grids [11] and their capabilities for smart metering and real time monitoring are necessary to address these challenges [23]. The smart metering and real time monitoring enable [24]: (i) increment of the automation and

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[1] Source: DNV KEMA: http://www.dnvkema.com/es/

coordination of producers, providers and consumers to balance supply and demand, (ii) response to the current market energy needs in real time, (iii) better understand of the electricity consumption, and (iv) reaction in real-time to sudden changes of the aggregated generation profile, in order to balance supply from intermittent renewable resources. Real time capabilities of Smart Grids stimulate new and changing behaviors emerges as a result of being able to acquire, store, distribute, process, and analyze data in real-time and to flexibly connect and disconnect resource. Therefore, this feature of Smart Grids reinforces its characterization as an *Evolutionary* SoS, in which behavior may emerge at any moment (*Emergent Behaviour*).

With regard to interoperability, Smart grids management requires dealing with huge amount of data from the volume of the data collected from smart meters and other devices connected to the power network. This data has a critical role in Smart Grids, and hence data interoperability is seen as the key enabler of Smart Grids. Interoperability at the physical layer of the grid can be defined as the ability of two or more devices from the same vendor, or different vendors, to exchange information and use that information for correct co-operation [26]. This co-operation at the upper layers of the grid not only means data interoperability but also services interoperability. Interoperability is required to guarantee the correct communication between the *Operational Independent* components and systems that constitute the grid.

From this analysis of the characteristic of Smart Grids, it is possible to conclude that Smart Grids accomplish the five criteria of a SoS, and its architecture design must be prepared to support these characteristic. Next subsections present an overview of our experience in Smart Grids and the architectural framework that has been defined to support the Smart Grids SoS.

3.1 Energos

ENERGOS (Technologies for the Automated and Smart Management of the Future Distributed Power Networks) is a CENIT Spanish project which goal is addressing these Smart Grid challenges [16]. Specifically, ENERGOS aims to construct the basis of a framework to support the design of Smart Grids by providing: (i) reasoning capabilities to the software components that conforms the grid, (ii) a real-time platform to integrate and manage the operations from those stakeholders involved in the Smart Grid (eg. consumers, producers, etc.), and (iii) guaranteeing interoperability in the information exchange among the components of the Grid. ENERGOS has constructed a platform to provide electric network with intelligence, whereas the real time constraints are respected and the interoperability among components is guaranteed. This platform has been the basis of the projects NEMO and IMPONET (see sections 3.2 and 3.3, respectively).

3.2 Nemo

NEMO&CODED (NEtworked MOnitoring & COntrol, Diagnostic for Electrical Distribution) is an ITEA project that focuses on the modeling, design, implementation and operation of networked hardware/software smart devices for the electrical distribution application domain. NEMO constructs a distributed infrastructure to enable dynamic Energy Efficiency services for low voltage electrical distribution in industrial and commercial assets. This infrastructure consists of an acquisition platform for collecting energy data in real time by guaranteeing the interoperability of their hardware/software devices, independently of their equipment or communication technologies.

3.3 Imponet

Smart grids management requires dealing with huge amount of data from the volume of the data collected from smart meters and other devices connected to the power network. This huge volume of data scales up the data management to a Big Data issue [27]. Currently, this data is gathered in large volumes from the meters along the day, and analyzed "off-line" in time-constrained periods (quarterly, hourly, daily and monthly). Therefore, electricity companies are demanding IT solutions to deal with the smart monitoring of power networks. The ITEA project IMPONET (Intelligent Monitoring of POwer NETworks) is focused on the smart and advanced control and monitoring of power networks to collect and store data and to measure the quality of electrical signals. Concretely, IMPONET has developed a flexible platform that allows the continuous monitoring of the network with real time or cuasi real time data processing and the configuration of the customer consumption profile to monitor its evolution and to make decisions based on its information. IMPONET platform has the capacity to respond in real time to the massive amounts of information that will be received from the network and to store them, as well as the signals that will have to be transmitted to the devices in the field. These results of IMPONET are supported by the results of ENERGOS and NEMO&CODED.

3.4 Architectural Framework for Large-Scale Smart Grids

Our experience and results obtained from the projects ENERGOS NEMO&CODED and IMPONET have allowed us to define an architectural framework for Large-Scale Smart Grids. This framework constitutes the basis for the construction of Smart Grids architectures. The framework consists of two dimensions: SoS Dimension and Common Systems Dimension (see Fig. 2).

Smart Grids are SoS of SoS due to the fact that a Smart Grid is composed of other SoS, such as solar farms, power plants, hospitals, wind farms, animal farms, industries, the swarm of electric vehicles, smart homes, etc [3][6]. These SoS that compose the Smart Grid constitute the SoS dimension of the architectural framework (see Fig. 2). This dimension is obtained from the managerial or stakeholders point of view decomposition of the SoS.

In addition to this SoS dimension, there is another dimension of the framework obtained from the functional decomposition of the SoS. This dimension has been called Common System Dimension, since these systems are common to most of the Smart Grids SoS. Therefore, these systems (Common Systems Dimension) crosscut the SoS Dimension (see Fig. 2). Previous works that present microgrids as SoS [7][22], has identified the Power System and the Management, Operation and Control System. However, due to the complexity that Large-Scale Smart Grids introduce, these systems must be extended and spitted in order to guarantee the scalability of an open and loosely coupled architecture [21] from the framework definition. As a result, we define as common systems: the Power System, the Control and Operation System, the Data Processing and Analysis System and the Stakeholder Service System (see Fig. 2). On the one hand, the *Data Processing and Analysis System* emerges due to the huge volume of run-time and historical data that must be managed in a

Large-Scale Smart Grid. On the other hand, the *Stakeholders Services System* consist of those services that are provided to the stakeholders of the Smart Grid (utilities, retailers, customers) in order to manage real time problems in a more efficient and safer way, to integrate the real time information on all corporate application, to monitor power quality, to configure of the customer consumption profile, to monitor its evolution, to make decisions based on its information, etc.

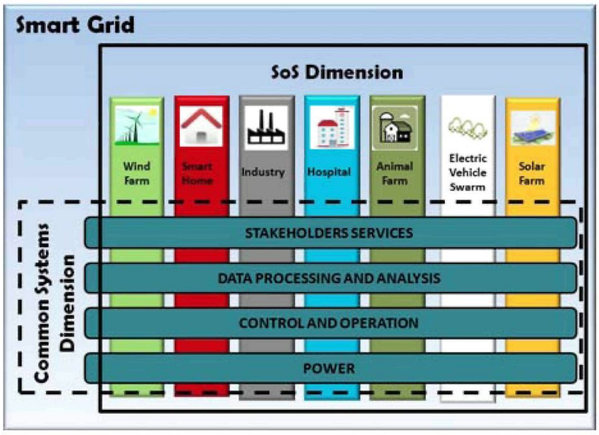

Fig. 2 Architectural Framework for Smart Grids

The deployment of this architectural framework for Smart Grids (see Fig. 2) must guarantee one of the emerging principles for SoS, which is: SoS architectures which are both open and loosely coupled tend to be more successful since they are tolerant of change in parts of the SoS and open to extensions to the SoS, with minimal impact on other parts [21]. From our experience, Service-Oriented Architecture (SOA) [28] is an approach that fits these requirements of the architecture. Therefore, the implementation of the resulting platforms of ENERGOS, NEMO&CODED and IMPONET are based on a SOA. This SOA is composed of four layers from top to down: Service, Component, Communication and Physical. These layers are deployed in the framework as it is illustrated in Fig. 3. The *Service layer* offers the services to the stakeholders of the systems. Therefore, it maps with the Stakeholder Services System. The *Component layer* implements software components that allow providing the services of the upper layer from the data acquired from the smart devices of the grid. This Component layer comprises both the Data Processing and Analysis System and the advance Control System, because they analyze data and behavior, and provide intelligence to the power network. The *Communication layer* facilitates the real time communication and enables the interoperability among the different devices that constitutes the power network, which compose the physical layer. Finally, the *Physical layer* must allow the connection and interaction of hundred of heterogeneous Intelligent Electronic Devices (IEDs) that are composed of thousands of data points. These IEDs of the Smart Grid surely have different languages and information models.

Finally, it is important to take into account that this SOA infrastructure (see Fig. 3) needs to be based on a set of standards and technologies for allowing: (i) the management, access and analysis of a huge variety of information, and (ii) the interoperability of the different IEDs. With regard to the huge amount of the data that the Data Processing and Analysis System of the Component layer should manage (see Fig. 3), we recommend using massive storage solutions (Big Data) [27], such as clustering technology Hadoop for batch data processing, and the integration with the SQL and NonSQL paradigms. This implementation approach has been validated through different smart grid scenarios obtaining the promising results of storage and processing, a billing profiling of 600.000 bills in less than 3 hours and calculate the best hourly value from a million of measure data points in less than 2 hours. With regard to the interoperability of data that must ensure the Communication Layer (see Fig. 3), the Smart Grid communications must be performed over a Unified Information Model. The Unified Information Model should integrate the most commonly used standards available in this domain, such as the Common Information Model (CIM) [25] standard or the IEC 61850 [26], in order to guarantee interoperability to the different actors that conform the Smart Grid. CIM is an abstract information model used to model an electrical grid and the different equipments used on it, whereas IEC 61850 was initially scoped to communications within the substation, although recently is also being applied to model de communication of smart meters. In addition, the Communication Layer must guarantee the real-time needs of a Smart Grids. This real time must be providing by extending SOA with what is increasingly known as “Extreme Transaction Processing Architectures” (XTPP). The basic objective of this architecture is to provide real-time capture and processing capabilities for massive amounts of information to all participating elements of the Smart Grid SoS. As a result, this architecture is implemented by using technologies of extreme processing XTPP and CEP (Complex Event Processing). Both the Unified Information model and the XTTP architecture of the Communication Layer provide the necessary support to the upper layers for data acquisition from multiple sources and dynamic modeling of the information integrated with massive storage solutions.

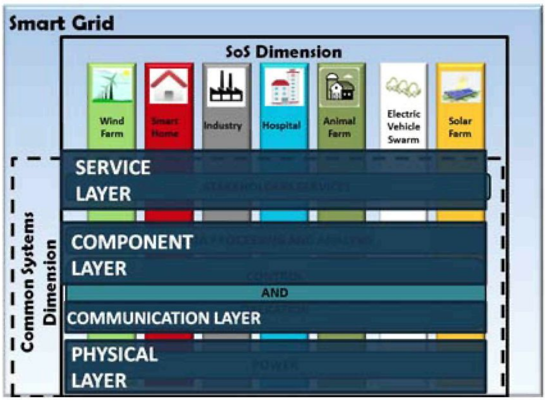

Fig. 3.Deployment of the Architectural Framework for Smart Grids

4. CONCLUSIONS

From the experience in the projects ENERGOS, NEMO & CODED and IMPONET, this paper conceptualized Large-Scale Smart Grids as a SoS of SoS and defines a two-dimension based architectural framework to deploy the software architectures of Large-Scale Smart Grids. This architectural framework considers the SoS that compose the Large-Scale Smart Grid—solar farms, power plants, hospitals, etc.—, but also the common systems that crosscut these SoS: Power, Control and Operation, Data Processing and Analysis, and Stakeholders Services. This architectural framework is based on SOA and a set of technologies and standards in order to guarantee the open, decoupling and interoperability requirements of SoS architectures. This architectural framework is a first step for defining an architecture of reference for Large-Scale Smart Grid SoS.

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