A Reference Model for the Electrical Energy System Based On Smart Grids

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***Abstract*—The development of Smart Grids, which has taken considerable momentum and efforts, is underway to implement rapidly systems that materialize concepts, that only few years ago were only ideas about how to develop a new electrical infrastructure with benefits for all actors and in particular for the end users. A number of projects that are underway do classify as Smart Grids but some rather implement conventional techniques. This paper presents a reference model that allows to clearly catalogue projects based on a layer approach similar as the OSI reference model that has been guiding communication development for about four decades. Specific rules based on the reference model to define what elements shall be part of Smart Grid project are proposed together with examples of typical projects that have been or are being implemented by utilities. The model is proposed to map interoperability issues, standards and other elements that in the proposed framework can be better understood for both technical and non-technical involved actors.**

***Index Terms*—Reference model, Smart Grid architecture, Smart Grid project, Smart Grid development, Interoperability.**

I. Introduction

THE development of complex systems is a task that normally takes considerable effort and time. Those systems are built by mankind to provide fundamental services for the society. Two of such systems are the electrical system, which was named "the most outstanding achievement of the XX century"[1] by the academy of Science of the United States; and the communication system providing us a number of benefits that were not present just some years before. The current electric system, with some improvements and changes mainly on the market side, was developed more than 50 years ago with a path that took more than 100 years. Several references present different aspects of the development of the electrical system with Smart Grids [2] [3] [4]. On the other side, only the telephone and telex are more than 50 years old, while the rest of the communication systems that we use today were developed in the last decades. This fast development of the communication industry has been possible by technological achievements and the early adoption of standards that were and, are still being developed, based on a common understanding of the different components that constitute such a complex system.

Among various other factors that have contributed to the development of communications, the early adoption of a Reference Model has been a key factor that has contributed to understand and explain the interaction of multiple elements that have been added during the years. Probably, the adoption of the model was not foreseen to accompany the journey of communications growth. It still remains as an important reference point that remembers the past but also supports the future.

Unlike communication system, the conventional power system has been developed thinking mostly in one single dimension: the physical. There, the analog variables explain the behavior of almost all the phenomenon that we can observe. We have used in the past, and are still using, equipment that have both analog input and output for the monitoring, control and protection of the system. The first centralized frequency controls were running on analog computers, the same as the first simulators of the dynamics of the system.

With the adoption of digital elements (those that use in one or another way a binary coding for transforming analog variables into digital strings) new forms of remote monitoring and controlling the system were designed and implemented. The early SCADA systems with terminal remote units used transducers and A/D converters feeding control systems for geographically dispersed assets. Today, these systems are still working although known as legacy systems. Based on data gathered by SCADA applications, such as the state estimator or dispatch applications, more and more sophisticated real-time control system were implemented starting in the 70's.

One important step towards the digitalization of the electrical power system was the introduction of the Intelligent Electronic Device, IED, allowing direct conversion of analog inputs, like voltages and currents, into digital variables and calculated results. The IEDs are nowadays used in the modern power plants, substations and field equipment to monitor, control and protect devices and systems. IEDs, with the appropriate protocols combined with communication and computer systems, are used to establish substation automation subsystems that have more computer power that most of the legacy control systems that were used for the national control dispatch.

This paper presents a conceptual Smart Grid reference model. A model is defined as "an approximation, representation, or idealization of selected aspects of the

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structure, behavior, operation, or other characteristics of a real-world process, concept, or system" by the IEEE dictionary [5].

First, a reference to the conceptual model that has been used by the Communication industry since 1979 is presented with a comparison of the communication and the power system to help understand the background that lies in the proposed model [6]. The model itself is presented with the seven layers that are proposed. Applications of the model for the explanation of different components of what is considered Smart Grid are presented using as input different projects that are based on recognized use cases taken form important references [9] [10]. The use of the model is further explained with the identification of standards that are considered key for interoperability.

II. Communications Reference Model

A. OSI Reference Model

Back in 1977, ISO recognized the special and urgent need for standards and heterogeneous informatics networks. The basic objective of the subcommittee in charge (SC16) was to standardize the rules of interaction between interconnected systems. After 18 months of discussions the Reference Model of Open System Interconnection (OSI) was developed. Fig. 1 shows the seven layers of the OSI reference model. Next, an overview [6] of the seven layers of the OSI Architecture is presented.

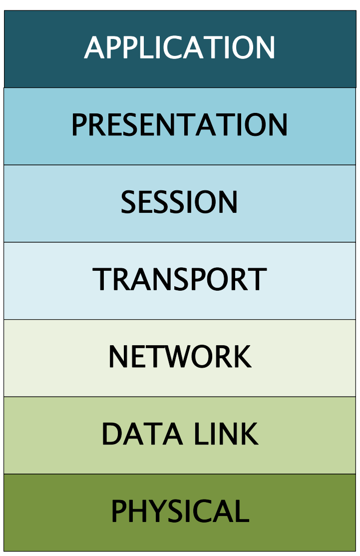

Fig. 1. OSI communications reference model

1) *The Physical Layer*. Provides mechanical, electrical, functional, and procedural characteristics to establish, maintain, and release physical connections between data link entities.

2) *The Data Link Layer*. Provides functional and procedural means to establish, maintain, and release physical connections between data links entities.

3) *The Network Layer*. Provides functional and procedural means to exchange network service data units between two transport entities over a network connection.

4) *The Transport Layer*. Provides transparent transfer of data between session entities.

5) *The Session Layer*. The purpose of this layer is to assist in the support of the interactions between cooperating presentation entities. The services are the binding of two presentation entities or the control of data exchange.

6) *The Presentation Layer*. The purpose of this layer is to provide the set of services which may be selected by the Application Layer to enable it to interpret the meaning of the data exchanged.

7) *The Application Layer*: Highest layer. An application is composed of cooperating application processes; with the purpose of managing a system. The management of an Open System Interconnection comprises those functions required to initiate, maintain, terminate, and record data concerning the establishment of connections for data transfer among application processes.

B. Parallel between electric and communication system

A comparison between the power system and the Information & Communications Technologies is presented in TABLE I.

TABLE I
COMPARISON BETWEEN POWER & ICT SYSTEM

Power System	**ICT**
Low information volume	High information volume
Non-efficiency-based	High efficiency due of digitalization
Non-differenced products into the network	Differenced products (voice, data) delivered into high complex networks
Analog product, vulnerable to internal and external factors	Digital product, low vulnerability to noise or environment (1 or 0)
Passive elements, require human coordination	Active elements, highly automated
Fixed- consumption orientation, low variability	Mobile consumer, high variability
Long life cycle components	Coexist naturally with obsolescence
Slow Steady growth	Constant multiplication of users

III. Proposed Model

A. Introduction

A model, as presented here, is a high level concept that through the use of various layers differentiates the various components of complex systems or implementations. As such a model can be used at various levels including:

- Identification of the various hardware and software components included in a project or system,
- Identification of project components that are implemented in a phased approach, which is normally the case for the deployment of Smart Grids,
- Identification of interface issues among the various components of complex systems,
- Identification of interoperability issues and solutions
- Differentiation of complex implementations that include solutions with different systems that complement each other towards a common task.

In the case of Smart Grid projects, the emphasis has been to the development of architectures rather than models. In this form implementations that address some issues of the architecture have been included as Smart Grid projects. However, the implementation of some isolated elements does no guarantee the development of sound long term solutions. In this form the efforts of some utilities that have implemented Smart Grid components without considering a global solution experience later technical interoperability and implementation issues, not speaking about extra costs. Also addressing interoperability issues early in the project conception helps to identify the necessary standards that need to be adopted or the risks associated with implementations that include not-standard based elements.

A model can be as complex as required, but those models that address the fundamentals rather than the details are those that simplify the views of a problem and help to define top-down solutions. Also when the model is not technology oriented it may be long lasting since it is technology neutral by nature being flexible to address today and tomorrow issues. Examples of other industries help to appreciate what and what not shall be included in a model for the Electrical Energy based on Smart Grid reference model as presented next.

B. Layers

Fig. 2 present the proposed seven layers model for the Smart Grids.

1) *The Physical Layer (P)*
Includes all physical elements of the power system and all the equipment that operate with analogical variables only: Generators, lines, transformers, analogical protection equipment, conventional energy meters, transducers etc.

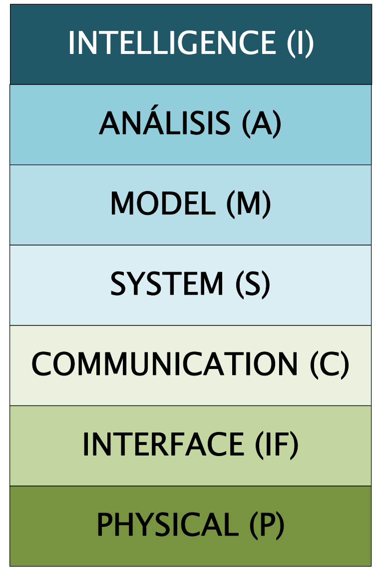

Fig. 2. Proposed reference model for the Smart Grids

2) *The Interface Layer (IF)*
This layer allows the connection and data transfer between the physical elements and the upper layers.
It is related to all the elements that allow passing from the analogical dimension to the digital dimension. For example, report the state of physical elements such as open/closed in digital format (0/1), or the digitized operation variables (voltage, current, power, etc.).

Fig. 3 show the transformation of analog variables to the "digital dimension", by means of devices like IEDs, PMUs, AMI and sensors.

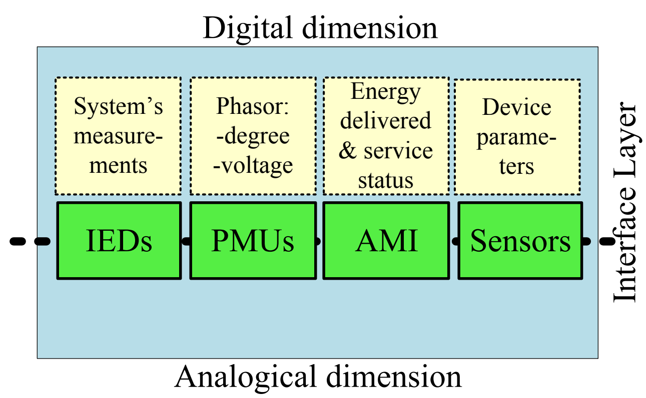

Fig. 3. From analogical to digital dimension

3) *Communication (C)*
Includes all the components that allow the data exchange between Smart Grid elements. Comprises the mechanisms that allow the communication such as protocols, for example, to send messages to the upper layers. It is supported by routers and other devices. There are several options to transfer data, such as fiber optics, cellular, power line carrier, wireless, etc., all of them carrying digital information loads.

4) *System (S)*
Corresponds to the set of devices and applications that collect data from the communication, interface and physical layers. This layer includes the functions of data processing (basic calculations) and generation and management of alarms, events and logs and historical data gathering.
Examples of systems are SCADAs (substation and centralized) and the Meter Data Management (MDM).

5) *Model (M)*
Comprises the abstract representation of the system, communication, interface and physical layer elements, to enable analysis and simulations by the upper layers. The Model can be as detailed as required, and is normally documented using modeling languages like UML. Examples of the model are the Common Information Model (CIM) and the modeling requirements of the IEC61850 standard.

6) *Analysis (A)*
Includes all the functions and applications for supporting the decision making by the operators, using real-time or historical data, from the system layer.
For example, a State Estimator uses data from the SCADA system to perform its own calculations and help the operator with consistent base cases supporting further processing by Contingency Analysis and Power Flow.

7) *Intelligence (I)*
The Intelligence Layer is the highest level of the proposed Smart Grid Reference Model. It includes advanced data processing applications such as data mining and highly automated processes not requiring human intervention. This last layer gathers data from several complex systems and applications to convert it into information and decisions. It supports complex metrics with dashboard functions. The ultimate applications like self-healing, or automatic grid operation, advanced adaptive protection and control applications are included in the intelligence layer.

IV. Model Application Examples

In order to illustrate the application of the model for various Smart Grid components selected common ones are presented. The reference model as presented shows its applicability to clearly identify components of complex systems in a layered structure, their relations and also where to define interoperability aspects between Smart Grid components such as applicable standards.

A. Energy Management Systems

Supervisory Control and Data Acquisition, SCADA, systems have been supporting the operation of power systems for more than four decades. The conception of early SCADAs has changed only slightly since the early implementations and most of the elements presented in obligatory references like [7] are still valid. Technology has improved data acquisition speed, data volumes and has provided SCADA services not only for transmission systems, with high voltages, but also for distribution systems, with medium voltages. Besides, the user interface of SCADA has improved dramatically, allowing operators to use more familiar tools, including geo-referenced data and other useful information. Complementing the SCADA system, applications comprised in the Energy Management Systems (EMS) suite of applications have been added since the late 1970's.

The EMS systems have provided tools that complement SCADA data when, for instance, data is missing due to communication failure, providing a base solution for the power system model, integrating redundant information (State Estimator), analyzing expected power system conditions for hypothetical faults (Contingency Analysis), providing recommendations for alleviating operating conditions that surpass power network limits (Optimal Power Flow), etc.

Fig. 4 present a simplified view of the SCADA/EMS components using the proposed reference model. In the Physical layer besides all the equipment of the electrical grid reside transducers that are used to gather analog variables and convert them to DC signals feeding Analog/Digital (A/D) converters that are part of traditional remote terminal units (RTUs).

Intelligent Electronic Devices (IEDs) were introduced later providing direct conversion of analog variables to digital data. Data Concentrators (DC) allow for gathering data from multiple local IEDs and provide for selecting operating data from IEDs to send them to the SCADA master station of the System layer using the Communication layer.

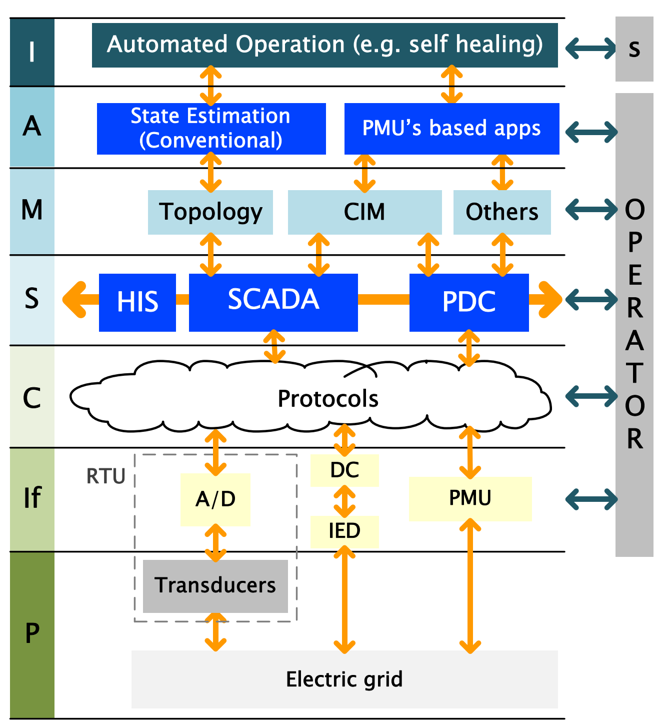

Fig. 4. SCADA/EMS System Model

RTUs and IEDs based SCADA systems coexist today and provide for conducting the control commands from the operators or from automatic means to the power network devices. Only recently Phasor Measurement Units (PMUs) have been added to the previously mentioned data gathering devices in the interface layer. PMUs also produce similar data as IEDs since their input are the same analog voltages and currents, but in addition to magnitudes provide phase angles that complement for certain applications the data required for enhanced power system monitoring, analysis, control and protection. The particularly high rate (30 – 100 samples per second, as opposed to the 1-10 seconds sampling rate of conventional SCADA) of these data and the need to time stamp them in order to obtain phase angle data with a high resolution is a characteristic of PMU data. Time stamps with 1 microsecond resolution allow for phase angle resolution of less than 0.02 degrees necessary for accurate PMU based applications. Due to these and other conditions for handling PMU data, this data is managed separately by data concentrators (PDCs) which are also considered to be part of the System layer. In the Model layer reside the models that represent mathematically all elements required for the analysis using the applications of the Analysis and Intelligence layers. As an example the State Estimator is an application that is part of the Analysis Layer while for instance Selfhealing automation future functions are considered part of the Intelligence layer. Other applications based on PMU data are considered to be part of the analysis layer. As shown the Operators with different functions interact with the equipment, applications and information or results of the six base layers. The intelligence layer is considered that will be mainly dedicated to implement algorithms that will allow to have the System to take decisions, that is implement the so called “autopilot” mode of the energy system control although with the possible human intervention when necessary.

B. *Advanced Metering Infrastructure System [7]*

The second example presents the various elements of an Advanced Metering Infrastructure –AMI System. AMI systems are implemented massively today in a number of utilities and countries being by far the most widespread Smart Grid implemented systems. Although AMI has different scope according with each project for this discussion it is considered that it comprises the utility components and also the interfaces to customer Home Area Networks – HAN.

Starting with the Physical layer where analog variables are gathered directly or using voltage and/or current transformers the basic single, two phase or three phase analog variables are converted to digital data using meters located at the Interface layer. The meter is connected to the used communication means which for remote communication may consist by fiber optic, Power Line Carrier, Wireless communication, etc. The Advanced Meter is considered also the communication point to the local HAN interface allowing for using the same remote data link for instance for direct load control and remote disconnection of the user. At the left the model represents the user HAN elements with its physical devices, HAN Interface to the metering system and the HAN Control which is considered part the the System Layer.

The Meter Data Management –MDM System gathers data from the advanced meters and provides this data to other systems for example SCADA. Meter models and related business models which depend on the markets where the meters are placed provide the necessary modeling framework so that the Analysis applications of the upper layer could perform their tasks. An example of typical applications being implemented is the Outage Management System – OMS. The OMS performs in conjunction with data gathered from the CIS and other applications the necessary functions for automatic detection of distribution system conditions, fault detection, fault isolation and system restoration functions. The Intelligence layer will accommodate automatic means for example for implementing advanced direct control of appliances in response to major system disturbances.

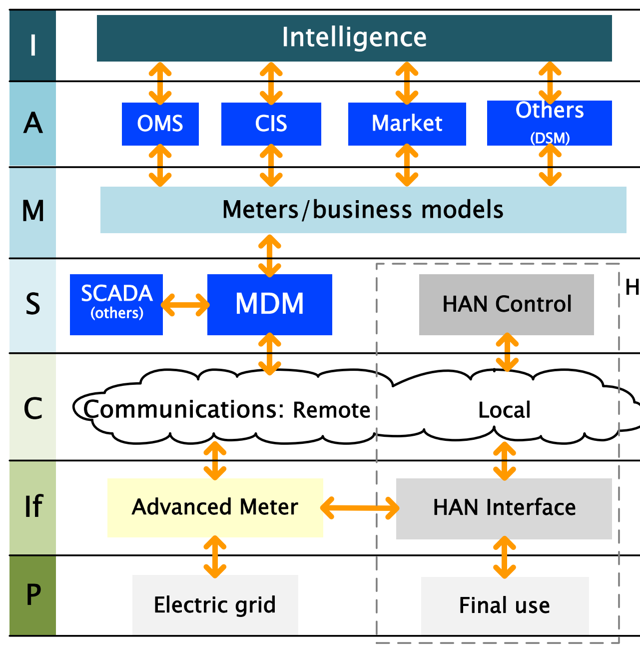

Fig. 5. Smart Grid Reference Model applied to AMI

V. SMART GRID PROJECT DEFINITIONS USING THE MODEL

Based on the model layers it is possible to differentiate Smart Grid projects from conventional ones which is one of the objectives of the Smart Grid Reference Model. For this purpose some basic rules are presented next.

- Rule 1: A Smart Grid project necessarily includes at least the following layers: Physical, Interface, Communication, System, Model and Analysis.
- Rule 2: An advanced Smart Grid project, in addition to the layers of Rule 1 includes also layer 7, Intelligence.
- Rule 3: If some existing layers are present due to previous implementations a Smart Grid project shall complement the existing layers with the layers required by Rule 1.
- Rule 4: A Smart Grid project may be divided in phases implementing different layers at different times. However

the project conception shall include at least the layers as per Rule 1.

The use of the previous rules applied to projects may assist in differentiating Smart Grid projects from conventional ones, assisting for example regulators and government agencies when making decisions supporting the development of Smart Grids.

Interoperability issues of the Smart Grid may be clearly identified using the model since most of the issues reside in the limits between the different presented layers. For instance the communication protocols that help to communicate data from the Interface layer to the upper System layers has been standardized for SCADA communications but is still under discussion for communicating meter data between the same layers. Also modeling issues such as those used by the Multispeak implementation differ from those proposed by the CIM model although convergence of these two approaches is under way. Furthermore, standards that are being developed for the smart grid can be easily be mapped to the model in particular for those that normalize the interfaces between proposed model layers. In this form the reference model may assist regulators and other actors to complement the views that have been proposed and are internationally accepted such as the Intelligrid Architecture of EPRI [11] [12] [13], among others.

VI. Conclusions

This paper presents a reference model that is proposed to accompany the development of Smart Grids. The reference model has seven layers and in a similar form as the OSI model adopted by the communication industry helps to better understand the various aspects that complex Smart Grid projects are implementing today. Typical examples presented illustrate the application of the model. Also specific rules to help the classification of the various aspects implemented by projects define when the project can be classified as a Smart Grid project or a conventional one. The concept of Advance Smart Grid is also introduced by the implementation of the seventh layer the Intelligence layer, allowing for further development of new forms of implementations that are yet to be formulated and implemented in the future.

The application of the model is believed will help government and regulators to better understand the scope of proposed projects, the complementary nature of different projects with similar focus but addressing issues of different layers, the normalization needs and the interoperability issues and solutions.

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VIII. Acknowledgement

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IX. Biographies

Renato Cespedes G. graduated as Electrical Engineer (1972) from the University of the Andes (Colombia) and obtained the Diplom and Doctor in Electrical Engineering (1976) degrees from the National Polytechnique Institute of Grenoble, France. He is associate professor at the National University of Colombia. Dr. Cespedes is presently partner and CEO of RCONSULTING Group, a consulting company based in Bogotá with interest in automation, technology and Smart Grid concepts. Dr. Cespedes retired in 2009 from KEMA Inc. where he held the position of Director of the Latin America operations. Dr. Céspedes is Senior Member of IEEE and has been chair of the IEEE T&D LA 2008 and IEEE ISGT 2011 Conferences. He is the author of a large number of publications on power systems analysis, control and operation and smart grids.