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A Survey on Smart Grid Technologies in Europe

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***Abstract*—The old electricity network infrastructure has proven to be inadequate, with respect to modern challenges such as alternative energy sources, security, electricity demand and energy saving policies. Moreover, ICT technologies development seems to have reached an adequate level of reliability and flexibility in order to support an entirely new concept of electricity network - the Smart Grid. In this work, we try to give a definition of what a Smart Grid is. Moreover, we will analyse the state-of-the-art of Smart Grids, not only in their technical details, but also in their management and optimization.**

***Keywords*-smart grid; renewable energy; grid intelligence; energy efficiency; energy storage;**

I. Introduction

Over the past 50 years, electricity networks evolved from the ”local grid” networks of the beginning of the century, to interconnected electric grids, based on generating stations of notable scale (1000-3000 MW) distributing power to major load centres, which divided energy to a large number of individual consumers. The generating stations, or power plants, were built in order to provide massive amounts of energy, due to the nature of power generation technologies in use (hydroelectric, coal, oil, and gas). By the end of the 20th century, however, this model proved to be unreliable and inadequate. First of all, the demand forecast techniques and the data processing technologies could not efficiently provide the desired energy at the desired time; thus, power distribution was based upon rough average classifications. Moreover, the emerging environmental issues and the geopolitical interdependence of power sources limited the development of economies of scale. The main challenges that a modern electricity network has to face are: [1]

- Privacy issues between energy suppliers and customers
- Security threats from cyber attack
- National goals to employ alternative power generation sources
- Significantly more complexity in maintaining stable power with intermittent supply
- Conservation goals that seek to lessen peak demand surges during the day so that less energy is wasted in order to ensure adequate reserves
- High demand for an electricity supply that is uninterrupted
- Digitally controlled devices that can alter the nature of the electrical load and result in electricity demand that is incompatible with a power system that was built to serve an analog economy.

These challenges require the development of an intelligent, self-balancing, integrated electric network that makes use of the modern ICT techniques to manipulate and share data. The Smart Grid technology tries to answer these needs.

In this survey, we propose an overview of the main aspects of Smart Grids development and implementation. In Section II, we give some definitions of the smart grid concepts, from different points of view. In Section III, we will analyse the management process of the Smart Grid. In Section IV, we will review its technical aspects. In Section V, we will see how a Smart Grid can be optimized. In Section VI, some conclusions are given.

II. What is a Smart Grid?

The Smart Grid is a complex system, and can be described in various ways. Here, we report two different definitions. The first one sums up the ”European” view of the Smart Grid:

”A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies. A Smart Grid employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies. Smart Grids development must include not only technology, market and commercial considerations, environmental impact, regulatory framework, standardization usage, ICT and migration strategy, but also societal requirements and governmental edicts.” [2]

The second one, written in the Statement of Policy on the Modernization of Electricity Grid of the United States Government [3], characterizes the Smart Grids by means of a list of achievements. The most relevant are: the use of digital information to improve reliability, security and efficiency; integration of distributed resources and generation; ‘smart’ technologies for metering, communication and automation;

deployment of energy storage technologies (i.e., electric vehicles).

According to [4] it is clear that both definitions combine two dimensions: kWh and bytes. It is not argued the key role of ICT in developing a smart grid, and both viewpoints recognize the growing role of renewable technologies, distributed generation and energy storage. In addition, both visions are focused on efficiency, but with different objectives: the U.S. definition is more energy intensive (and therefore less efficient) than the European one, which sets mandatory targets mainly in energy consumption reduction. The main differences consist in current and future business models: on the European side, unbundling and retail competition will be predominant; on the contrary, the U.S. side will be predominantly characterized by vertically-integrated monopolies. As a result, the European vision will lead to a greater complexity in the definition of business cases, and in a redesign of the industry value chain.

III. Business Management

The development of a Smart Grid does not involve replacing the existing electricity network. Such a process would be impossible for technical and economical reasons. Instead, the Smart Grid development is an enhancement of the existing network, by means of implementing new services and features, while maintaining, as much as possible, the old physical infrastructure. We have to define what functions a Smart Grid must provide. According to the United States Department of Energy's Modern Grid Initiative report, [3] these functions are:

- Self-healing
- Consumer Participation
- High Quality Power
- Support for different types of storage and generation
- Higher efficiency

The Smart Grid Technology also changes radically the Energy Market scenario: new actors may arise, such as Energy Retailers and Traders, Distributed Generation operators, and so on [5] (see Figure 1).

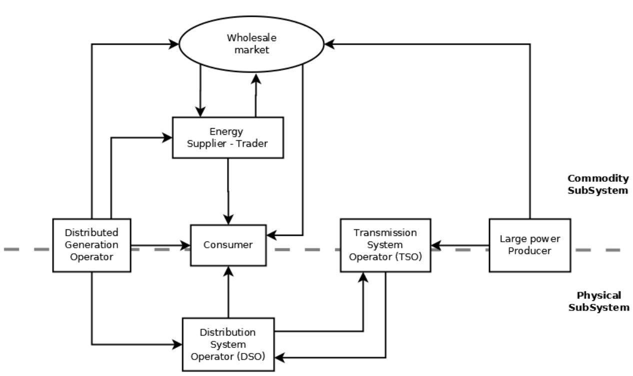

Figure 1. Overview of transactions within the electricity market. [5]

In [6], authors describe three elements as the "pillars" of the Smart Grid. Those elements are:

- *Smart Customer*: the set of technologies that enable consumers to observe and control their consumption
- *Smart Utility*: the utility that implements monitoring, control and pricing, and demand response
- *Smart Market*: an economically efficient market structure to integrate technology, decision making and information

Authors also identify Real-Time Pricing (RTP) as a fundamental tool to realize the Smart Market, because it provides consumers with a transparent way to control their energy bill, and utilities with a rate flexibility that allows them to increase their competitivity and implement Demand-Side Management.

In this new scenario, the roles of producer and consumer get closer. The consumer is now able to produce energy, through distributed renewable energy sources. This new emerging entity is called the *prosumer*, which is discussed in [7]. Authors define it as an economically motivated entity that:

1) Consumes and produces power
2) Operates a small or large power grid, thus transports electricity
3) Optimizes the economic decisions regarding its energy utilization

The prosumer may not be strictly a physical entity, but rather a combination of components: energy sources, loads, an electric grid, controls to operate his system, and a market, or other economic decision making system.

This new market must be supported through a management system that takes into account these new figures. An example of a strategic approach for a complete energy management system is BEMI (Bidirectional Energy Management System). [8] BEMI is an energy management system designed for installation at Low Voltage grid connection points. Its main task is to optimize the so-called Controllable Distributed Electrical (CDE) units, which means locally connected loads or generators. This optimization is done accordingly to consumption and generation tariffs, set by an energy service provider through a Pool-BEMI system. BEMI supervisions the CDE unit switching and operation, and also provides grid costumers complete information about the variable tariffs, energy cost and device schedules. The BEMI System is shown in Figure 2.

Another project worth to be mentioned is SmartGen [9], an Italian project driven by several industries and two different research institutes (University of Bologna and Genova). This project aims at finding and implementing industrial solutions for Smart Grid management. The authors propose the definition of a DMS (Distribution Management System) for each portion of the grid, able to control and optimize power flows, distributed generation and load balancing. The

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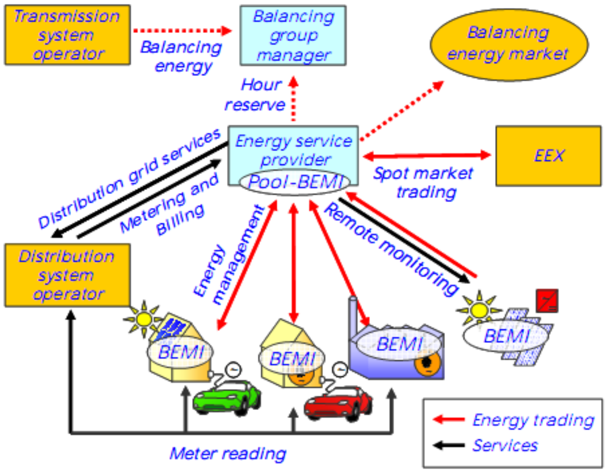

Figure 2. BEMI System in the liberalized energy market. [8]

base function of a DMS can be divided into:

- Supervisory Control and Data Acquisition (SCADA);
- Control Stations

The SCADA system provides specific monitoring and real-time control operations, in an automated way, while the Control Stations allow human operators to interact with the system.

IV. TECHNOLOGY

In this section, we will review some technical aspects of the implementation of a Smart Grid and its features.

A. *Distributed Generation*

Distributed generation (DG) is a driving factor for the Smart Grid implementation. Its integration in the energy network proved to bring many benefits [10] for customers, energy efficiency, and network operation itself. This integration is enabled through a number of different technologies [11], some of which are discussed in this survey:

- Advanced Metering Infrastructure (see Section IV-B)
- Energy Storage Systems (see Section V)
- Advanced Distributed Management Systems (see Section III)

In [11], authors provide a methodology for integration of DG in a Smart Grid Network. It is based upon the connection of a distributed generator with a feeder, combined with an Automatic Voltage Control (AVC) system and a Dynamic Line Rating (DLR) function. In their study, they also provide an economic feasibility study, as a series of steps, which may be extended to a general project involving DG technologies. The defined steps are:

- Define the installation, operation and maintenance costs of the project
- Define additional financial parameters like electricity rates, discount rates, inflation rate, etc.
- Quantify additional benefits brought to the network, in terms of a premium to the electricity rate per output unit
- Evaluate externalities, such as Greenhouses gases (GHG) reduction, to add them as a benefit
- Calculate the economic parameters internal rate of return (IRR) and net present value (NPV) to evaluate the feasibility of the project.

B. *Metering*

In order to efficiently implement a Smart Grid, a smart metering infrastructure is essential. Traditional metering devices, provided by energy distribution companies for their customers, typically measure energy consumption only in terms of total energy consumed, thus not giving any information about when and how it is consumed. This information can lead to a more intelligent energy provision, finely tuned to suit specific customer needs - and optimizing energy distribution over all the network. In this context, it is impossible not to cite AMI (Advanced Metering Infrastructure). AMI features include [12] [13]:

- Two way communication to the electric meter to enable information interchange
- Self registration of metering points
- Auto-configuration after a failure in communications
- AMI system interconnection to utility billing, outage management systems, and other applications

In [12], the authors name the integration between Smart Grid and AMI as AGI - standing for Advanced Grid Infrastructure. The AGI has the following enhancements [12]:

- **Outage**: *Improved Customer Service*
  Utilizing the AMI infrastructure, a utility can know when an outage occurs. The AMI system can notify the trouble call system automatically, facilitating rapid crew deployment and reduced outage times.
- **Loss Detection**: *Improved Network Operation*
  By connecting information nodes at key points of the medium voltage distribution lines and distribution transformers, it is possible to directly calculate the system technical and non-technical losses. This enables better tracking and efficiency on the distribution network.
- **State Estimation**: *Integration of Renewable Sources*
  By utilizing information from the customer site, medium voltage lines, and transformers, accurate load models can be computed allowing accurate load estimation on the distribution grid. This information is critical to understanding the impact and benefit of connecting renewable energy sources to the distribution grid.

Also in [14], a more detailed view of the AMI infrastructure is given.

An open issue regarding metering is determining power consumption of ICT equipment. According to [15], ICT technologies have a relevant impact over power consumption. Thus, the problem of finding precise models and figures to calculate and estimate this consumption has become a priority for the professionals of the sector. In [16], authors expose a case of study regarding the analysis of power consumption data from a data center, in a time period of about a year. The analysis was mostly focused on servers, which represent the main ICT power consuming device in these structures (if we exclude cooling and illumination). This work has shown that, undoubtedly, software has a relevant impact over servers' power consumption (up to 10%). This means that, in order to correctly forecast ICT power consumption, many factors have to be considered, such as the usage profiles of the equipment.

C. Forecasting

Forecasting is a key functionality of a Smart Grid system. Through forecasting, the Grid is able to balance loads, optimize power distribution and handle failures. The main problem of forecasting, in a modern electricity network, is given by the Renewable Energy Sources (RES). The energy produced by RES can vary, and its variation depends on several parameters (climate conditions, source plant location, etc.) In this sense, their contribute in terms of energy can be difficult to predict, because the variables to observe are too many. In this sense, it is worthy to cite the work of Bertani et al. [17], where is presented a central dispatcher with the following functions: short-term forecast of the power produced by renewable energy sources (RES), short-term load forecast and day-ahead load profile prediction, distribution system state estimation, day-ahead economic dispatching and on-line scheduling of the optimal distributed resources' operating conditions. The forecast algorithm was based on a neural network. The results can be seen in Figure 3.

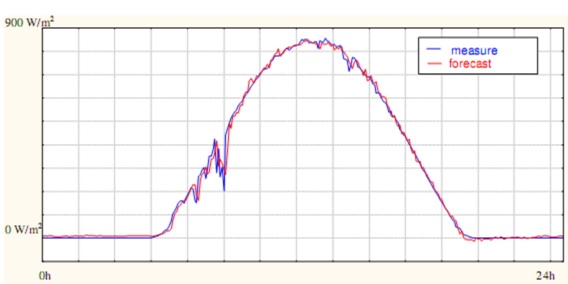

Figure 3. Example of forecasted vs. measured global radiation. [17]

D. Communication

A key issue for successfully realizing the future-oriented energy system is integrating information and communication on an Internet-based infrastructure,able to provide access to energy information in a simple, quick and economic way. This is because energy providers, either centralized or decentralized, need a constant flow of real-time updates regarding the energy demands, in order to provide the precise amount of energy needed. Optimization of energy consumption is based on integrated and near-real-time electronic communication between producers and loads on all levels of the grid.

This infrastructure will also be profitable for consumers. In fact, by developing intelligent end devices, customers will be able to monitor their actual power consumption in real time, and consequently they can optimize the usage of their devices in order to reduce costs. [18]

An example of integration between the Smart Grid and the ICT is a solution proposed in [19]. In modern energy distribution systems, generation and demand need to be always matched in real-time. This means that the modern grid is a real-time distributed system, thus it needs a precise synchronization between its devices. Modern grid infrastructures realize several functions, such as protection testing, fault detection, load balancing and scheduling through synchronization. The authors propose a solution based on the implementation of the Network Time Protocol (NTP) over 802.11 networks along with an optimisation technique to reduce the energy usage of a common Wireless Sensor Network (WSN) synchronisation protocol. [19]

The Service-Oriented Architecture (SOA) provides concepts particularly suitable for an energy distribution network. In fact, it decouples functionalities from implementation, integrating them through message exchange protocols in a dedicated Service Bus. Moreover, it is not needed to develop interfaces between every application: each application only needs to be interfaced to the integration platform.

The only issue of the SOA is finding the correct semantics for data. Without open interface definitions and a standard semantic structure for message exchange, it is not possible to realize an efficient energy network.

Web Services are especially useful in the context of Smart Houses. An Energy-Aware Smart House is a residential building equipped with a Smart Metering system (see Section IV-B) able to measure and control in real-time the power consumption of every electrical device installed. In [20], a Web-Oriented Application Framework for embedded devices is presented. The framework is based on a RESTful architecture.The embedded devices represent sensor nodes, which may provide all sort of information (power consumption, for instance). This solution has shown a response time for querying each device lower than 60 ms, even with high workload.

The suitability of Web Service architectures for the Smart Grid/Smart Houses is also stressed in [5].

V. OPTIMIZATION

In this section, we will present how a Smart Grid network can be optimized through new technologies and approaches.

A. Agents

A Smart Grid is, by itself, a decentralized network, where intelligence is distributed across several devices. These de-

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vices may have to take autonomous decisions, in order to react quickly and efficiently to changes in energy demands, faults, and such events.

Thus, the Software Agents paradigm may provide a way to implement a system like that. In fact, in this paradigm, it is possible to design a distributed system with specific functionalities through the cooperation of autonomous, intelligent components.

In [21], authors present a Multi-Agent System (MAS) simulating a Smart City. The simulated entities were:

- Houses
- Appliances (Single devices, of different classes, installed into a house)
- Vehicles (Electric Vehicles able to store energy into batteries)
- Cities
- Power Stations

The system was implemented using JADE (Java Agents Development Environment). Each entity was represented by a software agent. Then, an energy controller agent is able to act in order to balance power demand and power generation (for example, turning off some devices when power consumption is too high). In Figure 4 are shown the results of the balancing activity. The proposed scenario involved 300 houses evenly divided into three cities, and a total of 3840 appliances.

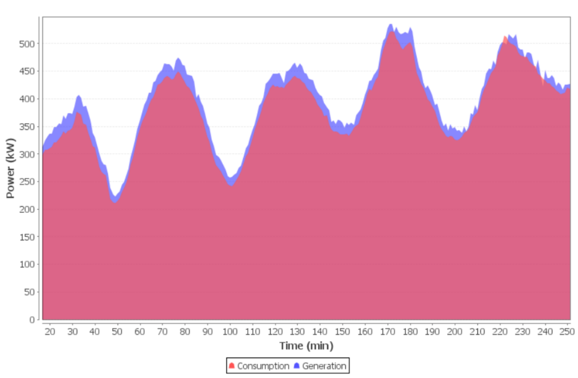

Figure 4. Consumption and generation chart [21]

MAS are often associated to *electronic markets*, computing frameworks for distributed decision making based on microeconomics and Game Theories. By applying this paradigm to the energy distribution networks, we can make use of the already developed techniques and methodologies to realize the so-called *Market-Based Control*.

Several works following this idea have been proposed. In [22], for example, a complex multi-agent architecture is presented, composed of different components: : the Problem Formulator and Attributes Evaluator (PROFATE), the Scenarios Builder, the Electricity Market Multi-Agent System (EMMAS), the Decision Making Assistant (DMA).

Of these components, the most interesting is without any doubt the EMMAS. In order to forecast market prices, both at medium and long-term, accurate simulation models are needed, able to react to structural changes. The EMMAS realizes these models, by means of a complex taxonomy of software agents that represent every actor in the transaction process

Another example of a MAS designed for controlling energy networks is *PowerMatcher*.

”The Power Matcher is a general-purpose coordination mechanism for balancing demand and supply in clusters of Distributed Energy Resources. These ’clusters’ might be electricity networks with a high share of distributed generation or commercial trading portfolios with high levels of renewable electricity sources, to name a few.
Within a PowerMatcher cluster, the agents are organized into a logical tree. The leafs of this tree are a number of local device agents and, optionally, a unique objective agent. The root of the tree is formed by the auctioneer agent, a unique agent that handles the price forming, i.e., the search for the equilibrium price. In order to obtain scalability, concentrator agents can be added to the structure as tree nodes.” [23]

B. Energy Storage

Another aspect that can substantially improve the efficiency of a Smart Grid is the energy storage. Basically, it is the problem of keeping energy available directly on the grid, in storage components efficient enough to avoid energy losses. In cases of energy production peaks, when there is an overproduction of energy, having a distributed storage system can increase the overall efficiency.

An agent-based solution is exposed in [24]. Basically, they propose a game-theoretic framework, that analyses the Nash equilibrium of an electricity network, and develops learning strategies for agents that dynamically adapt to the energy market. As regards storage devices, they embrace the so-called Vehicle-to-Grid (V2G) view, where the unused energy is stored in the batteries of electric vehicles (EVs) or Plug-in Hybrid Electric Vehicles (PHEVs). Since this solution can raise problems of peaks in energy demand, a Multi-Agent System is adopted in order to optimise usage and storage of electricity. In particular, the proposed system models a situation where each device is represented as an intelligent software agent, and every agent can try to ”buy” the needed amount of energy at every time, meanwhile learning which is the most profitable amount of energy to buy, according to the specific usage. The authors claim that, implementing their solution, a single consumer may save up to 13% on his electricity bill. [24]

C. Unit Commitment Problem

One of the key objectives of a Smart Grid architecture is dispatching energy from all the available sources in order to meet the electric load. In other terms, there is a problem of coordination between energy demand and generation. This problem has been formalized under the name of Unit Commitment. Unit commitment (UC), also known as pre-dispatch, is the problem of scheduling the production of energy by generation units of a power system. The objective is to minimize total production costs, while observing several operating constraints. Thus, UC is a complex mathematical problem, based on both integer and continuous variables. In order to solve this problem, an optimized algorithm is needed, because complete enumeration of all the possible solutions would require excessive computation time. [25] For this survey's purposes, we analysed two possible solutions, which involve different approaches for solving the Unit Commitment Problem. In [26], authors propose a solution based on Adaptive Dynamic Programming (ADP).

The solution presented by the authors focuses on a specific family of ADP: the Heuristics Dynamic Programming (HDP).

"The implementation is divided into ***action network****,* ***critic network*** *and* ***model network****. The function of* ***action network*** *is to determine the feasibility region of operation of the power systems and to detect the emergency state with corresponding violations under different contingencies. The function of* ***critic network*** *is for post-optimization process, evaluation and assessment of control options during contingencies. And the function of* ***model network*** *is to read power system parameters and obtain distribution function for state estimation of measurement errors inherent in data, ascertain and improve accuracy of data. The aim of all these kinds of methods is to approximate the cost-to-go function which is relative to the output of critic network."* [26]

Another approach for the UC problem is presented in [27], where the authors introduce a solution using Genetic Algorithms (GAs).

The application of the GAs to the UC problem included encoding each solution with a simple binary alphabet. At first, a number of initial binary-coded solutions (*genotypes*) are produced randomly to form the initial population. Then, a fitness value is given to each solution, calculated as a sum of penalties for violating certain problem constraints. Afterwards, a new offspring genotype (new solution) is produced by means of the two basic genetic operators: *crossover* (combining different solutions by mixing their binary codes) and *mutation* (modifying randomly chosen bits of the offspring genotypes. The above procedure is repeated until a new set of genotypes is produced, which is considered as the new generation of solutions. The new generation totally replaces the parents. By also implementing some adjustments to the fitness calculation, the GA technique has proven to converge in the order of hundreds of generations.

VI. Conclusions

In this work, we surveyed the Smart Grid project from different points of view, analysing the efforts that the scientific community is making to implement this infrastructure. We presented complete management solutions, communication systems, and different kinds of optimization techniques.

One of the facts that this survey has shown is that, from a technological point of view, there are plenty of solutions already available. Several management systems have been tested and are ready for deployment. However, another fact is evident: although many different standards exist, especially for data communication and protocols, few of them have been widely accepted for application in energy distribution networks. To give an idea of the problem, below some of the standard communication protocols are listed:

- Application Level:
  - IEC TS62351 (data and communication security)
  - IEC 62443 (safety)
  - IEC 61968 (integration of applications into electricity supply facilities)
- Transport Level:
  - IEC 61850 (Station automation)
  - IEC 62055 (Electric Meter)
  - ISO/IEC 14543-3(KNX)
- Communication Media Level:
  - IEC 60255 (Protection Installation)
  - IEC 81334 (PLC)

This can be an issue, because one of the keys to an efficient energy network is interoperability between different energy providers. A partial solution can be using Web Services and system integration techniques, but there has to be a standard definition for data structures and models in order to enlarge the scope of the network. The biggest obstacle to standardization, and in general to Smart Grid implementation in Europe, from our point of view, is given by the complex situation of the European energy market, where regulated and liberalized regimes still coexist. In regulated markets, the main grid operator establishes a monopoly business, that does not allow consumers to choose among different technologies, as regards, for example, metering services, forecasting, and so on. Also, energy retailers, although present on the territory, are not able to assume their innovative role in the Future Energy Market depicted in Section III, in terms of demand response, consumer services and network operation.

As far as it concerns the research activity, what should be done is embracing a common view of the problem, focusing on interoperability and supporting the creation and affirmation of technology standards. In this way, the development of solutions and optimization techniques can be immediately followed by field testing and deployment, speeding up the overall infrastructure realization process.

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