An Overview on the Smart Grid Concept

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***Abstract*—Smart Grid is a concept for transforming the electric power grid by using advanced automatic control and communications techniques and other forms of information technology. It integrates innovative tools and technologies from generation, transmission and distribution all the way to consumer appliances and equipment. This concept integrates energy infrastructure, processes, devices, information and markets into a coordinated and collaborative process that allows energy to be generated, distributed and consumed more effectively and efficiently. This paper reviews some researches and studies on Smart Grids (SGs) technology.**

***Index Terms*—Smart Grid (SG), Distributed Generation (DG), Renewable Energy Sources (RES), Computational Intelligence (CI) methods, High Voltage DC (HVDC), Flexible AC Transmission System (FACTS) devices.**

I. Introduction

POWER generation and distribution systems are facing new significant challenges leading to wide investigation efforts in different directions aiming to increase the use of sustainable and renewable energy sources (RES).

In accordance with international targets for the environment, RES applications can offset the dependence on fossil fuels, provide green power options for atmospheric emissions curtailment and contribute to peak load shaving. In the long term, they will contribute to mitigate climate change impacts. This will require new optimization methods for energy resources dispatch since they are inherently distributed together with interconnection standards and operational constraints. Nevertheless, the stability, reliability and cost implication of RES should be taken into account.

The Smart Grids (SGs) technology can support integrating RES in future power systems. A SG has been defined by the Smart Grids European Technology Platform as "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 supply" [1].

The primary goal of a SG is to deliver the optimal amount of information and load control for customers, distributors and grid operations in order to reduce system demands and costs while increasing energy efficiency.

The SG concept is naturally associated to the production of energy through the use of RES as the SG promotes social benefits like reduced emissions, lower energy costs, and greater flexibility to accommodate new renewable distributed energy sources. These results can be achieved by the integration of many different technologies including Information and Communication Technology (ICT) necessary for making the energy demand and production more predictable and controllable.

An important characteristic of the smart grid concept is its "active" nature. Active Network Management (ANM) forms one area of work within the SG concept and is expected to emerge as the preferred solution for the connection and operation of distributed generation (DG) in the near term. ANM is concerned with the connection and operation of DG in real-time network constraints and can be efficient in network development for connecting increased levels of RES and DG. More background on ANM is available through an on line database of activities [2].

ANM in the UK, for instance, has been examined through the work of the Embedded Generation Working Group [3] and solutions for individual generators have been proposed in [4]. ANM includes the management of distribution network constraints to support the extension of DG and RES. The most recent literature on the active distribution networks proposed methods for managing the system in order to make better use of available resources [5]-[13]. Siano et al. [7] evaluated the maximum wind energy exploitation in active distribution networks using a multi-period OPF method including coordinated voltage control, energy curtailment and power factor control.

Active networks will revolutionize the current passive electrical system and an "Internet-like" model, with distributed decision-making systems constitutes the final goal to reach in the long term [5]. During the initial stage ANM will allow DG and RES monitoring and remote control, in order to facilitate their integration in the system, then it will permit accommodating significant amount of DG and RES once local and global services and trading issues will be defined.

The active power management will be based on network management by using real-time communication and remote control. ICT based systems, state observation methodologies and identification techniques will be required in order to develop innovative strategies able to estimate both changes in system parameters and to carry out real time automation [14]. In order to design a reliable, highly secure, and manageable SG, open communication infrastructures connecting the parts of the grid and distributed intelligence will be required.

SGs are expected to provide self-corrective, reconfiguration and restoration to handle with load variability and market participants in real time. This result can be achieved using intelligent equipments, ad-hoc communication protocols and smart routing algorithms, thus dealing with very complex systems. The purposes of SGs design are to create controllable assets, to increase the power system performance, security and reliability and decrease operations costs [1]-[14].

In this paper some researches on SG technology are reviewed. Section II, reviews some recent international programs on SG definition, design and applications, Section III discusses some issues related to power electronic converters, Section IV deals with control methods of SG while section V introduces computational intelligence (CI) methods for SGs optimization. The role of SGs for the next generation electric vehicles is discussed in Sections VI. Design and planning, smart metering, economic aspects and liberalized market issues of a SG are introduced in Sections VII, VIII, IX, respectively. Conclusions are given in Section X.

II. Some research activities on Smart Grids

In the following some of the most important international researches on SG are described.

The tasks of the IntelliGrid program, initiated by Electric Power Research Institution (EPRI), are the creation of the technical foundation for a SG that links electricity with communications and computer control to improve reliability and customer services [15]-[18]. This program can provide methodologies for open standards and requirement-based technologies with the exploitation of advanced metering, distributed automation, demand response, and wide area measurement.

GridWise [19] is a vision, developed by the Department of Energy and industry contributors, based on the opinion that a basic conversion of a power system to an intelligent, adaptive and self-healing network with market-based structures for creating profits at all levels of the system requires information, communication and control technologies in the whole system.

The National Energy Technology Laboratory set up the Modern Grid Initiative (MGI) [20] that pointed out that policy and technology actions are required to allow the modernization of the electric system in the US. The SG strategies are based on the integration of existing technologies that can enable the fundamental characteristics of a modern grid.

The Distribution Vision 2010 consortium is matching the advancement of new technologies to provide the achievement of automated distribution systems. Automation and advanced distribution systems give an option for higher reliability and operation of a SG.

The SG program, established by the European Technology Platform (ETP) in 2005, built a joint vision for the European networks of 2020 and beyond [21]. According to this program the European electricity networks should be flexible to requests of customers, available to network users and renewable power sources, secure and endowed with high quality of power supply.

III. Power Electronics Applications in Smart Grids

Present power systems, consisting of few conventional large power plants, will be integrated by thousands small energy conversion systems (ECS), often located close to loads, capable of autonomous operations, grid connected or isolated Since the power system is continuously changing its structure, sources and loads, the development of very flexible ECS is needed. Distributed Energy Resources (DERs) that can be installed in a SG are usually not suitable for direct connection to the electrical network due to the fluctuating characteristics of the produced energy, often affected by voltage and frequency fluctuations and poor power quality. For such a reason, energy conversion systems, based on power electronic devices, are required. Advancements in the field of power electronics in combination with modern control strategies for inverters offer a variety of operation strategies for efficient system management [1]. The inverter is considered the basic component in the optimization of RES and DER, since it is the active control element at the connection point between the sources and the grid. Future inverters need to be flexible and must be able to support any local conditions. SGs claim integration as the basic needs for a secure future power supply [22].

In the field of power electronics applications in a SG, Flexible AC Transmission System (FACTS) and High Voltage Direct Current (HVDC) will be helpful to provide fast dynamic voltage control, power flow and stability control of the power grid while increasing efficient utilization of transmission assets [23]. The combination of FACTS and HVDC control with Wide Area Stability Control and Protection Systems will exploit control capabilities of both technologies to achieve fast stability control of the SG and to avoid the system blackouts. The voltage control devices consist of shunt reactors and shunt capacitors, tap-changing transformers, synchronous condensers, synchronous generators, Static Var Systems (SVS), Converter-based FACTS controllers such as Synchronous Static Compensator (STATCOM), Static Series Synchronous Compensator (SSSC), Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC), Generalized Unified Power Flow Controller (GUPFC) and HVDC light. Mostly, the Converter-based FACTS have excellent dynamic reactive power and voltage control capability. If suitable damping controllers will be designed, FACTS devices can accomplish appropriate damping for small signal disturbance. Recently, Linear Matrix Inequality (LMI) technique received attention in the design of FACTS based damping controllers. The LMI approach has been suggested for the design of robust damping control of FACTS such as $H-\infty$ mixed-sensitivity [24], [25]. Advanced components are used in the SG including next generation FACTS, power quality devices, advanced energy storage, fault current limiters, superconducting transmission cable and rotating machines, advanced power electronic switches and conductors. These components can be helpful for the system at several levels [26].

IV. Control and Automation for Smart Grids

Advance integration of telecommunication, sensing, control, and optimization have been recognized to help achieving adaptive interaction, self-healing, efficiency and reliability of a SG. Figure 1 shows a summary of the major functional elements to be considered in the SG design. Power systems control depends on the accessibility and sensor measurements quality. Faults caused by broken or bad connections, bad communication, sensor failure may, in fact, give rise to failure of power system controllers and consequently lead to severe contingencies. Fault-tolerant technologies will be needed in a SG to improve its reliability and security and advanced control methods should accomplish real-time forecasting by using computational intelligence methods. These methods provide applications such as monitoring and data gathering from sensors and analyzing data to detect and provide solutions. Intelligence in a SG is required in all levels, it would be required to endow each substation and power plant with a processor that monitors and communicates with other ones via smart sensors. The required real-time data required by wide area monitoring and control systems will be provided by smart sensors and sent to the system main controller that should be much faster and more accurate than traditional Supervisory Control and Data Acquisition (SCADA) control systems.

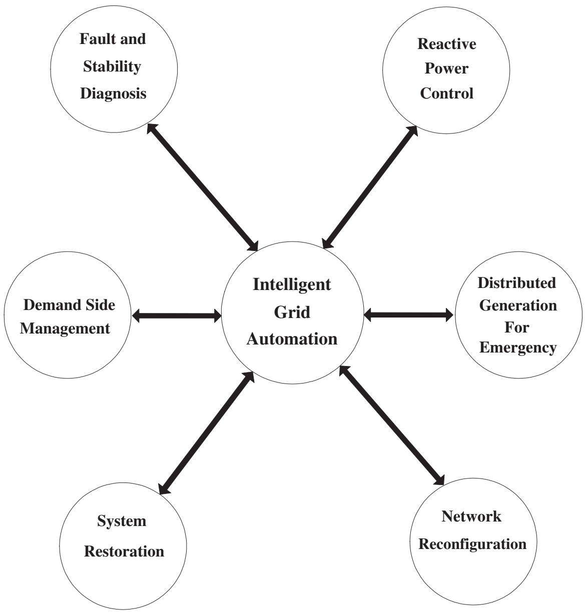

Figure 1. Smart Grid Intelligent automation functions.

The increasing complexity and nonlinear nature of future SG will require, in particular, fast and accurate on line monitoring systems such as a wide area monitor (WAM) and effective control systems such as adaptive wide area controller (WAC) [27], [28]. A WAM is essential for SGs in order to carry out functions such as self-healing, fault-tolerance and dynamic optimization. An optimal WAM system, based on a radial basis functions (RBF) neural network has been developed in [29] to identify the input-output dynamics of the nonlinear power system. A WAC is designed based on a WAM by using a dual heuristic programming (DHP) method and RBFs, while considering the impact of delays of signal transmission. The WAC acts as a global controller to coordinate the actions of local controllers including those on a wind farm. Each local controller connects with the WACand receives remote control signals from it, thus improving system dynamic and transient performances.

A. Control Methods for Smart Grids with DG and RES

Due to increasing energy demand and the move toward clean energy production, DG based on RES had a large growth in the last decade. Wind Turbine (WT), Photo Voltaic (PV), and combined heat and power (CHP) systems are set up at different levels in distribution power systems. Generally, a PV power plant is operating always on maximum power point, deriving the maximum power accessible from the panels, while the storage unit performance is ruled by energy prices. Output power from the storage device can be controlled by the central supervisory controller for achieving various requirements in the grid. A supervisory controller should take care of the optimal power flow, volt/Var optimization in the grid and should dispatch the energy generated by DGs according to network constraints [30]. WTs have various remote control options with regard to active power control such as maximum power control, power limiter control, delta control, balance control [31], [32]. Timbus et.al. [33] demonstrated that local controllers of DGs and a supervisory control, performed by a distribution management systems, can communicate with each other based on standardized data models. Moreover, a system-wide supervisory coordination of DERs was implemented to optimize the scheduling of the production of wind energy and CHP, while respecting capacity constraints and minimizing the total operational cost. For efficient, secure and reliable operation of a SG, voltage control and VAR management require various voltage control devices installed at different locations of the systems. Voltage control, previously carried out only by conventional power plants, should be coordinated by means of SCADA systems. DG should fully participate in voltage control which is still not coordinated. and this feature will be very important for SGs implementation.

V. Computational Intelligence Methods

Computational Intelligence (CI) can endow smart grids with innovative, powerful and effective tools summarised in Fig. 2.

CI adaptive methods can contribute to achieve intelligent behavior in complex and changing domains. These adaptive approaches include artificial intelligence paradigms able to learn from experience [34] that can be combined to form hybrid methods resulting in Neuro-Fuzzy systems, Neuro-Swarm systems, Fuzzy-Particle Swarm Optimization (FPSO) systems, Fuzzy-Genetic Algorithm (GA) systems, Neuro-Genetic systems, ant colony optimization and immune systems, etc. The challenges that are facing the CI include structure of neural network, learning method, training range, long convergence time, etc. There are several CI applications for the SG including energy and power flow management algorithms. Adaptive design tools and PSO-based fuzzy logic have been demonstrated to carry out optimal energy dispatch in a grid

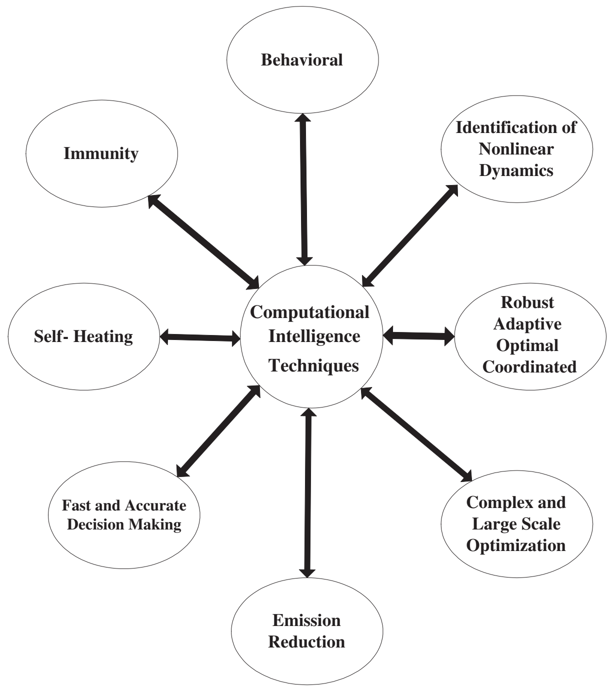

Figure 2. Capabilities of Computational Intelligence Methods for Smart Grids [38].

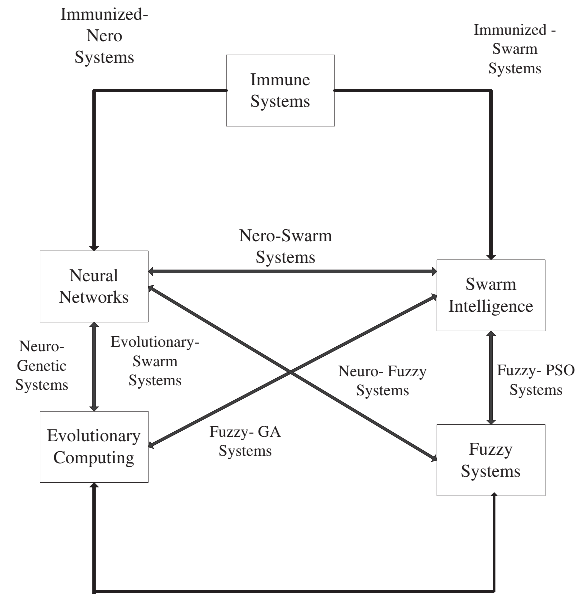

Figure 3. Typical Paradigms of Computational Intelligence Methods [38].

with a photovoltaic system [35]. The successful use of CI methods for control of voltage and reactive power control and stability has also been demostrated [36], [37]. The typical paradigms of CI are illustrated in Fig. 3 [38].

VI. Electric Vehicles and Smart Grids

As in the next years there will be millions of decentralized renewable power sources, the role of the grids is becoming very significant in order to balance the energy demand variations with the variable power generation from RES. Moreover, the grid operators will employ advanced energy management approaches to supply a huge number of public and private remotely metered recharging stations where plug-in vehicles can charge/discharge [17], [39]. For organizing optimal usage of stored energy in these vehicles, innovative intelligent methods will be required. These vehicles, when parked, can inject power to the grid, known as vehicle-to-grid (V2G), or absorb power from the grid to charge the batteries, known as grid-to-vehicle (G2V) [17], [18].

VII. Design and Planning methods for Smart Grid

Distribution network expansion planning is concerned with determining an optimal network configuration which can meet electricity demand, within safety and operational constraints, at a minimum cost. Investments on the network are made to develop the network due to the growth in demand or the renewal of ageing assets [40]-[49]. In some cases, network development investment with DG, active management schemes and energy storage will be more complex. Many approaches to find an optimal network expansion planning have been reported such as mathematical optimization methods and heuristic planning methods [41], [42], multiple objective methods [43], evolutionary optimization techniques [44]. In [45] stochastic programming has been introduced as a potential decision support tool to aid network planners in the long-term expansion planning process. Recent progresses in Artificial Intelligence have developed Adaptive Dynamic Programming (ADP) as an approach to manage complex power system problems with prediction under uncertainty conditions [41]. Development of Stochastic Optimal Power Flow (DSOPF) as a computational tool in design of SG has been extended in [46].

VIII. Smart Metering and Demand Side Management

A SG generally involves the application of smart meters, sometimes called advanced metering infrastructure (AMI), which usually includes control and monitoring of devices and appliances. Smart metering technology will be the foundation of any SG design [50]. The most viable communications technologies for the AMI are wireless and power line communication (PLC). Power distribution companies have traditionally been interested in PLC because it represent the most cost effective solution and does not require additional investment in the communications infrastructure [51]. Narrowband PLC systems appear to be well suited to implement the SG due to their inherent low cost. Bannister et al. [50] have shown that the Orthogonal Frequency Division Multiple Access (OFDMA) protocol, which combines frequency diversity and “orthogonality” with a multiple access scheme, offers a more robust solution to the problems of narrow-band communications systems. Costumers will have the chance to decrease their electricity bills by changing consumption from higher-priced hours to lower priced hours [51] and smart metering will produce a market for new SG costumer products.

IX. Economic Aspects and Liberalized Market Related in a Smart Grid

A SG can decrease the amount of electricity consumed by houses and buildings and accelerate the connection of RES to improve the reliability, security and healthy living of electrical infrastructure. Advanced communication equipments, the enhanced knowledge of customers and local electricity supply management systems, enabled by smart metering and electronic technologies, will play an important role in employing new services. Combination of ICT and business processes will be significant tools in the real time management of active networks, customers and commercial systems. Deregulated markets will let consumers to utilize information to move between competing energy suppliers based on energy cost, greenhouse gas emissions and social goals. A SG vision for the market has been developed in recent years through the work of a consortium of utilities. One option is an “eBay for electricity”, where continual electronic sales match energy consumers with energy producers. One of the tasks of a regulator in the electricity market is to endorse the tariffs that a system operator charges to its clients on the basis of a satisfactory level of service. The major complexity in this task is the irregularity of information that exists between the regulator and the system operator even if numerous remuneration schemes exist for system operators [52], [53].

X. Conclusion

This paper makes a first and partial attempt to review previous researches on SGs principal issues. It’s worth pointing out that the SG implementation will require a huge amount of economic investments and further researches. Moreover, additional commercial arrangements and financial evaluations have to be set up. New market rules are required for providing new revenue mechanisms to share the benefits as well as the costs due tothe SG realization between DG developers and system operators.

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