Artificial Intelligence Techniques for Smart Grid Applications

María-José Santofimia-Romero, Xavier del Toro-García, and Juan-Carlos López-López

The growing interest that the smart grid is attracting and its multidisciplinary nature motivate the need for solutions coming from different fields of knowledge. Due to the complexity, and heterogeneity of the smart grid and the high volume of information to be processed, artificial intelligence techniques and computational intelligence appear to be some of the enabling technologies for its future development and success. The aim of this article is to review the current state of the art of the most relevant artificial intelligence techniques applied to the different issues that arise in the smart grid development. This work is therefore devoted to summarize the most relevant challenges addressed by the smart grid technologies and how intelligence systems can contribute to their achievement.

Keywords: Artificial Intelligence, Computational Intelligence, Dynamic Grid Management, Smart Grid.

1 Introduction

The structure of traditional electrical grids comprises different stages in the energy supply process. The first stage consists of the power generation that takes place in large power plants. In the second stage the energy is transported to the areas where it will be consumed. Finally, after being adequately transformed, energy is delivered to the end user in the distribution stage. This last stage in particular has experienced many changes in recent years with the progressive introduction of new players such as distributed generation units (mainly wind and solar farms and co-generation plants), the expected growth of storage systems and the future introduction of the required infrastructure to recharge electrical vehicles (see Figure 1). These new players are bringing new possibilities and more flexibility in the way energy has been traditionally managed. Nevertheless, the resulting system requires the introduction of new advanced technologies to cope with the increased complexity.

In the most recent decades, the world has experienced a very significant increase in energy consumption and a generalized concern about future energy problems and sustainability has arisen. This situation has led governments and the scientific community to look for solutions that allow an efficient, reliable and responsible use of energy, appealing to an optimized and more flexible conception of the electrical grid. This new paradigm is known as the smart grid. Despite the wide spectrum of technologies encompassed which makes it unfeasible to provide a simple and unique definition, it is quite common to consider the smart grid as the framework that integrates all the advanced control and information technologies to monitor and manage power generation and distribution. There are many common aspects between the conception of the smart grid and those principles that enabled the Internet, as it is known nowadays [1]. Indeed, it is quite usual to conceive smart grid

Authors

María-José Santofimia-Romero received the degree of Technical Engineer in Computer Science in 2001 from the *Universidad de Córdoba*, Spain; Master's degree on Computer Security from the University of Glamorgan, Wales UK, in 2003; and the degree of Engineer in Computer Science in 2006 from the *Universidad de Castilla-La Mancha*, Spain. She is currently working towards her PhD as a member of the Computer Architecture and Networks Research Group (ARCO) at the *Universidad de Castilla-La Mancha*. <mariajose.santofimia@uclm.es>

Xavier del Toro-García received the degrees of Technical Engineer on Industrial Electronics and Engineer in Automatic Control and Industrial Electronics in 1999 and 2002, respectively, from the *Universitat Politècnica de Catalunya*, Spain. He received a PhD degree from the University of Glamorgan, UK, in 2008. From September 2005 until October 2006 he was a Marie Curie Research Fellow at Politecnico di Bari (Italy). Since 2008 he has been working as a researcher at the *Universidad de Castilla-La Mancha*, Spain. His research interests include power electronics, renewable energy sources, energy storage systems and power quality. <xavier.deltoro@uclm.es>

Juan-Carlos López-López received the MS and PhD degrees in Telecommunication (Electrical) Engineering from the *Universidad Politécnica de Madrid*, Spain, in 1985 and 1989, respectively. From September 1990 to August 1992, he was a Visiting Scientist in the Dept. t of Electrical and Computer Engineering at Carnegie Mellon University, Pittsburgh, PA USA. His research activities center on embedded system design, distributed computing and advanced communication services. From 1989 to 1999, he has been an Associate Professor of the Dept. of Electrical Engineering at the *Universidad Politécnica de Madrid*. Currently, Dr. López is a Professor of Computer Architecture at the *Universidad de Castilla-La Mancha*, Spain, where he served as Dean of the School of Computer Science from 2000 to 2008. He has been member of different panels of the Spanish National Science Foundation and the Spanish Ministry of Education and Science, regarding Information Technologies research programs. He is member of the IEEE and the ACM. <juancarlos.lopez@uclm.es>

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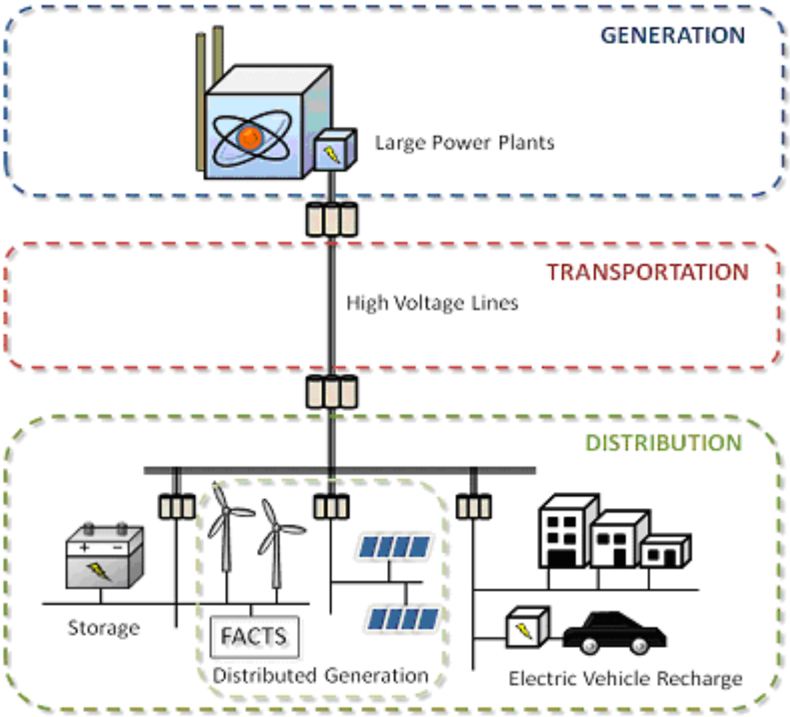

Figure 1: Electrical Grid Structure and Evolution.

technologies as traditional grids enhanced with information and communication technologies providing an efficient, safe and reliable use of electricity.

For a more in depth view of the smart grid, some of the concrete goals that smart grid technologies aim to achieve are listed below:

- To provide prompt response to changing conditions in the electricity network,
- To foresee electricity network behavior (consumption peak demands, faults, etc.),
- To improve the power quality that finally gets to the clients,
- To provide security guarantees (privacy, prevention from attacks or deliberate disruptions, etc.),
- To provide fault-tolerance and self-healing capabilities,
- To integrate different and distributed renewable energy sources.

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Some of these challenges mainly result from the need to mitigate the impact that grid failures and power quality disturbances have on industrial and domestic customers. Furthermore, besides the economical concerns, reducing carbon emissions as a step towards sustainable development seems to be of major interest for the driving forces of the smart grid development. In this sense, the use of renewable energies is gaining relevance as technological improvements are being achieved. Nevertheless, there are still several major drawbacks which are preventing them from being massively deployed. Renewable energies, such as solar power and wind power, are not distributable power sources that can quickly respond to the grid operator’s energy demands due to their intermittent nature. Moreover, the amount of energy that can be generated cannot even be predicted and scheduled even though considerable improvements have been achieved in short-term production forecasts. These important drawbacks can only be overcome by integrating alternatives in the generation mix, interconnecting large grids, an improved scheduling of the generation and consumption times and the introduction of energy storage systems.

Another important fact to be considered is that future smart grids will also need to allocate power to electrical vehicles to allow sustainability in terms of mobility. The electrical infrastructure required for a large deployment of electrical vehicles will have a big impact on the electrical infrastructure and the consumption profile. Nevertheless, it will bring new opportunities since a bidirectional energy

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flow in the vehicle battery is possible, the so-called Vehicle-to-Grid (V2G) concept, and electrical vehicles can therefore be seen as a distributed storage infrastructure that can contribute to the stability of the grid.

Considering the complex scenario previously described the smart grid challenges can be summarized into three main groups [2], namely:

a) Technological challenges,
b) Economic challenges,
c) Regulatory challenges.

Technological challenges basically address the attainment of distributed communication strategies with optimized latency and bandwidth, advanced control systems, reliable fault tolerance management techniques, efficient massive data processing methods and new energy storage devices. Regarding the economic challenges, new business models arise from a new way of conceiving the upcoming energy market. For example, active demand response strategies help in reducing peaks of consumption in the power system by temporarily changing and shifting the consumption patterns followed by users, either by increasing or decreasing their consumption at certain times of the day. Finally, the regulatory challenges are related to the establishment of standards that, at different levels, specify the basis for interoperability required to make smart grids feasible.

Despite the highly diverse nature of the aforementioned challenges, they share a common set of features that need to be considered as the starting point to propose solutions based on computational systems. Such systems should be capable of dealing with evolving, uncertain, variable and complex scenarios. In order to do so, as stated in [3], computational systems need the capability to understand the ongoing situations, make decisions, and re-evaluate the situations to determine whether further actions are required.

This article presents a survey of the wide spectrum of computational intelligence systems that are contributing to address the existing challenges of future smart grids. Section 2 reviews the different smart grid technology areas distinguishing between those that can be considered mature enough to be deployed nowadays and those in an early stage of development. Sections 3 and 4 analyze the role that the different computational strategies, agglutinated under the perspective of Artificial Intelligence, are playing in developing smart grid systems. Finally, Section 5 summarizes the most relevant ideas presented in this article.

2 Smart Grid Technologies

In order to evolve towards a smarter grid, research and development efforts must be concentrated in the following key technology areas [4]:

- **Wide-area monitoring and control.** Wide-area monitoring and control systems (WAMCS) assume the responsibility for preventing and mitigating the possible disturbances that might strike the grid. In order to do so, WAMC systems perform advanced operations intended to identify the presence of instabilities, aid the integration of renewable sources, or improve and increase the transmission capabilities. WAMC systems consist in the centralized processing of data that have been collected from distributed sources in order to evaluate the state of the grid. The main functions of a WAMC system are carried out in three different stages, namely: data acquisition, data delivery, and data processing [5].
- **Information and communication technology integration.** An essential aspect of the smart grid is the need for real-time information exchange that has to be based on some sort of communication infrastructure able to support the integration of distributed and heterogeneous devices.
- **Integration of distributed renewable generation systems.** Distributed generation consists in the integration of many small power generation sources at the distribution level. When those sources of generation come from renewable sources, additional challenges arise due to the unpredictability and controllability issues associated with the resource availability. Nowadays, distributed generation based on renewable energies is quickly gaining presence in some countries, in which stability and power allocation problems are arising. In a long term, research efforts start to be noticeable in the field of energy storage systems, as a mean to alleviate the drawbacks associated to the existing decoupling between energy generation and consumption.
- **Transmission enhancement applications.** The electricity transmission stage is responsible for migrating the bulk power obtained from the generation plants to the distribution substations. Current research efforts are being addressed to increase the transmission capacity by resorting to different applications such as Flexible AC transmission systems (FACTS), high-voltage DC (HVDC), high-temperature superconductors (HTS), or dynamic line rating (DLR).
- **Distribution grid management.** The idea behind the technological solutions intended to support the distribution grid management is that of providing communication improvements throughout the different components of the distribution system. The main applications of the technologies provided for distribution grid management are intended to perform tasks such as load balancing, optimization, fault detection, recovery, etc.
- **Advanced metering infrastructure.** Those technologies encompassed under the umbrella of advanced metering systems are intended to provide enhanced functionalities other

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than just metering or counting. Probably, the most well-known application of the advanced metering infrastructure is that of the dynamic pricing, intended to help consumers to reduce their bills by adjusting their consumption to those periods outside the peak demand times. In order to do that, an advanced metering system is composed of three components: the smart meter, the communication utility, and the meter data management application [6]. It should be noted that the distributed character of the components comprising the advanced metering infrastructure brings to light a growing concern for it is the need for standards that helps to overcome interoperability problems.

- **Electric vehicle charging infrastructure.** One of the main tenets of the smart grid is that of using a more sustainable conception of the power generation and consumption process. In order to do so, it is a priority to minimize the emission of green-house gases and electric vehicles provide a solution in response to this concern. Moreover, the role electric vehicles can play in the smart grid is also relevant with regard to its capability to work as a storage unit.
- **Customer-side systems.** Customer-side systems encompass those applications that are intended to make more efficient use of electricity as well as a cost reduction for the customer. Energy management systems, storage devices, smart appliances and small generation systems (i.e. solar panels) fall into this category.

This section has summarized the most relevant aspects of the different technologies that are encompassed under the umbrella of the smart grid. Each of these technologies, simultaneously, is articulated by a wide set of applications, some of which have been succinctly mentioned. The next section focuses on those specific applications, and how computational intelligence can contribute to narrowing the existing gap between contemporary grids and the envisaged smart grid.

3 Artificial Intelligence and the Smart Grid

In light of the most common activities undertaken by smart grid systems, it can be stated that there is an association between the smarter grid conception and the Artificial Intelligence paradigm. Indeed, rather than appealing to the Artificial Intelligence paradigm in all its aspects, the focus may be directed upon distributed intelligence efforts [7].

The main challenge to be tackled in the smart grid comes from the vast amount of information involved in it. In contrast to traditional grids, in which the consumption metering information was only retrieved monthly, smart grids present a new scenario in which all the interconnected nodes are gathering information about many different matters, and not only consumption (i.e. real-time prices, peak loads, network status, power quality issues, etc.) [8]. In this sense, one of the main challenges for computational intelligence is how to intelligently manage such an amount of information so that conclusions and inferences can be drawn to support the decision making process. This challenge is being mainly addressed from the perspective of Complex Event Processing (CEP) techniques.

CEP techniques address event filtering to seek for relevant patterns. However, the selected events need to be semantically enriched in some way so that they can lead to an understanding of the ongoing situation. CEP systems need to be complemented with more sophisticated techniques that support the understanding process. In this sense, one of the possible approaches is the use of Qualitative Reasoning. In [9] an example of this approach employs a qualitative behavioral model of the electric grid, in which some power quality issues such as voltage dips and reactive power are modeled in order to anticipate their possible evolution and negative effects. Problems related to power quality provide an interesting field of application for monitoring and diagnosis tasks. The cited work [9] tries to bridge the gap that leads to self-sufficient systems, capable of anticipating and reacting to power faults from simple data gathering. In order to so, the proposed approach provides a characterization of the power quality problem, presenting a qualitative behavioral model of the grid dynamics. This model supports a multi-agent system in charge of anticipating and reacting to power faults and disturbances.

In the same way, more complex reasoning systems can also enhance smart grid technologies. Those reasoning systems based on large-scale knowledge base of common sense, such as Cyc [10], Scone [11], or ConceptNet [12], can provide advanced capabilities to assist and enrich *Supervision, Control and Data Acquisition* (SCADA) systems.

Achievements in the context-awareness field can be easily extrapolated to fulfill certain valuable functionalities of the smart grid. For example, *Dynamic Line Rating* technology is in charge of maximizing the distribution lines by dynamically reconfiguring the line capacity of the different grid sections, taking into account external conditions such as the weather. In this sense, further knowledge about the surrounding context can lead to a more efficient and sophisticated use of the distribution line. Additionally, *Active Demand Management* technology addresses the problem of providing the right amount of electrical power at the right location and time. This task involves some sort of load balancing, in which the Artificial Intelligence planning and knowledge-based techniques can contribute with important improvements [13].

Nevertheless, information management is not the only

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requirement for smart grids that benefits from the strengths of artificial intelligence techniques. On the contrary, several smart grid technologies resort to a wide variety of intelligent solutions to tackle uncertainty and unpredictability. For example, the *Active Network Management* technology can resort to intelligent agents so as to address the automation of activities such as voltage and frequency control, reactive power control, fault detection and fault ride-through, or self-healing. Provided that this technology requires a communication infrastructure to support the SCADA system, achievements in intelligent distributed systems can be of a great help. In this regard, the distributed systems theory can contribute with algorithms, communication approaches, or consistency and replication techniques, among other possibilities. In particular, Multi-Agent Systems (MAS) can be considered as a sort of intelligent distributed systems that can find a very suitable field of application in the smart grid due to the distributed and heterogeneous nature of the problem [14]. As it is illustrated and discussed in [15] and [16], MAS have been successfully used in a wide range of power engineering applications.

4 Computational Intelligence and the Smart Grid

The previous section has surveyed the most relevant approaches of Artificial Intelligence that have been applied to the smart grid in order to tackle the existing challenges. This section continues this survey paying special attention to those techniques that have been specifically devised to address dynamic and stochastic problems.

There are two main approaches when it comes to dealing with scenarios that are unpredictable or uncertain, the artificial intelligence and computational intelligence techniques (see Figure 2). Despite the fact that at first glance, both approaches might seem to be equivalent, artificial intelligence and computational intelligence techniques differ in the way they approach complex problems. Artificial intelligence techniques adopt some sort of goal-oriented approach, in the sense that problems tend to be grounded in thorough descriptions of the world and associations can be established between the problem to be solved and the actions that can help in achieving the desired state. However, this approach for complex problems is not very suitable for situations in which stochastic processes interfere. The *openness* of these scenarios is better addressed by means of computational intelligence techniques, comprising well-known approaches such as evolutionary computation, fuzzy logic, or artificial neural networks. The common aspect of these approaches is that solutions, rather than being provided as a result of previous knowledge stating actions attached to goals, they resort to stochastic processes consisting in iterative cycles of generation and evaluation. Traditional artificial intelligence techniques experience difficulties when several goals are in conflict with each other. In contrast, computational intelligence techniques perform well under such circumstances.

The role that computational intelligence can play in the smart grid environment is therefore grounded in its capability to enable intelligent behaviors under uncertainty conditions [17]. This section is therefore devoted to reviewing the most successful techniques as well as the potential challenges that those techniques will be able to address.

The main contributions of computational intelligence techniques to the field of smart grids are identified in [18]. The most interesting feature of these techniques is their ability to anticipate relevant information that assists the decision making process. Additionally, these methods provide the means to control the grid in a reliable and rapid manner.

Artificial Neural Networks (ANNs) consist in the replication of the operation of biological neural systems [19]. In this sense, a neural network comprises a collection of interconnected nodes that are nothing else but processing units that have associated two values, an input and a weight [20]. The most characteristic feature of the neural networks is that rather than being programmed to perform certain tasks, they can be trained to identify certain data patterns. During the training phase the neural network is provided with input data and targets to learn the recognition of certain patterns. Nonetheless, their main advantage also turns out to be their main drawback since these methods require from a large amount of input data that needs to be representative enough for generalizing behavioral patterns [21].

The work in [20] surveys some of the most relevant applications of ANN techniques to the field of energy systems. These applications range from a wide variety of purposes such as, modeling solar energy heat-up response [22], prediction of the global solar irradiance [23], adaptive critic design [24], or even for security issues as reviewed in [25]. The idea behind these applications is based on learning how system performances can be related to certain input values, for instance, how weather conditions (solar or wind) determine the energy output that can be expected [26].

Voltage stability monitoring [27] applications are among the most successful contributions of ANNs to the smart grid technologies. In this sense, the work in [28] presents an innovative method to estimate the voltage stability load index using synchrophasor measurements of voltage

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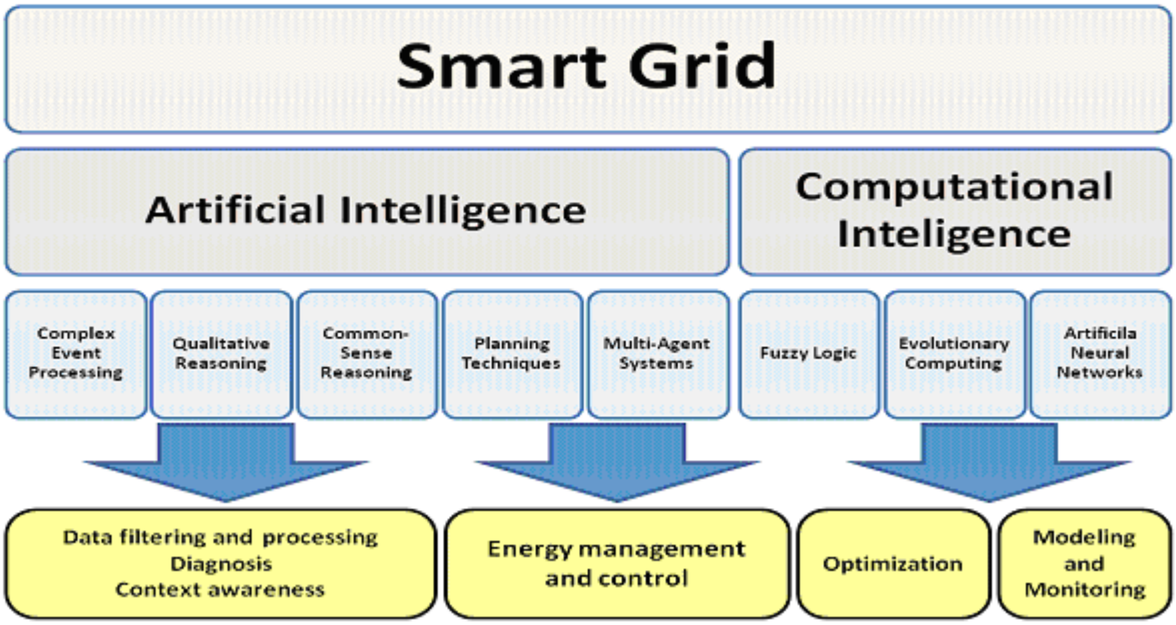

Figure 2: Artificial Intelligence and Computational Intelligence Techniques and their Contribution to the Advanced Features of the Smart Grid.

magnitudes and angles.

Wide area monitoring applications do also benefit from the potential of the ANN-based methods. The work in [29] describes the implementation of a system intended to identify the dynamics of the non-linear power system. Neural networks have demonstrated their capability to detect in real time the changing dynamics of power systems. Whenever such changes are identified, an additional ANN can be employed to generate the appropriate control signals that minimize those negative effects [30].

Evolutionary algorithms (EA) [31], and more specifically genetic algorithms, have gained great relevance due to their capability to successfully address optimization problems with a relatively low demand of computational resources. Genetic algorithms are inspired in the evolutionary principle of natural selection [32] and they consists in the encoding of a set of plausible solutions, as though they were the initial population, out of which the fittest members are favored to create the next generation of solutions. This methodology is intended to remove, in recursive iterations, those solutions that are considered poor. Additionally, the work in [32] provides a list of the different applications of genetic algorithms in the field of the energy systems. A specific example of an application can be found in [33], which resorts to a genetic algorithm method with a twofold aim: firstly, a genetic algorithm is used to generate a feasible solution, constrained to the desired load convergence and secondly, a genetic algorithm is used to optimize the obtained solution. The work in [34] also resorts to a genetic algorithm approach for efficiency enhancement, demonstrating that those fuzzy controllers implemented by means of genetic algorithms obtained optimum results (both for entire and discrete time intervals).

Finally, the last approach considered in this review of computational intelligence methods is Fuzzy Logic (FL) [35]. There are many processes in the smart grid that in-

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volve decision-making tasks, for example, deciding how to allocate renewable energy production, or when to consume on the light of the energy price market evolution. The fact that FL methods attempt to provide solutions to control problems based on approximations, resorting to a system representation that rather than using conventional analytical and numerical calculations, uses simple labels to quantify inputs and simple rules based on "IF-THEN" statements. FLs have demonstrated outstanding performance for decision-making processes with estimated values under uncertainty conditions [20]. Additionally, FL methods have also been implemented in a long list of energy system applications, such as supervision and planning tasks in the presence of renewable energy sources as the work presented in [36, 37].

5 Conclusions

The growing concerns about the environmental impact that energy corruption is having on the planet are leading to a new conception of power systems, in which renewable energies are increasingly integrated into the production cycle and also in which energy efficiency and security should be maximized.

This work has paid special attention to how artificial and computational intelligence can contribute to the achievement of smarter grids. To this end, this work has reviewed the main smart grid technologies and the current and potential impact that intelligent approaches have upon them.

It can be concluded that knowledge-engineering approaches can successfully address the problem of managing the vast amount of information that will be generated in future smart grids. Additionally, distributed intelligence techniques can provide the means to monitor and manage all the different stages involved in the whole process. Multi-agent system approaches have demonstrated their capability to cooperate and articulate responses to the distributed data coming from the different sources of information. Finally, the role of computational intelligence or soft computing techniques, can greatly contribute to the optimization and control process involved in the smart grid.

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