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Short survey

Methods for the management of distributed electricity networks using software agents and market mechanisms: A survey

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ABSTRACT

Significant research efforts are being devoted to the development of distributed electricity networks that aim to facilitate the gradual integration of manageable loads and distributed energy resources. These environments are conceived as self-managed, enclosed areas of the distribution network that integrates many of the technologies and information systems that will be part of the future Smart Grid. Both the new scheme and devices are expected to offer users presence in the grid operation so that their preferences and interests are relevant. To this end, the management system has been frequently proposed in form of an electronic market in which producers and consumers exchange energy blocks so that the consumption and production are continuously balanced. As the state of the art reflects, intelligent agents are an suitable technology for building energy management systems in which users participate actively in an intelligent and autonomous manner. This document presents a review of the most relevant works that tackle the safe and effective management of distributed electricity networks through autonomous software agents that negotiate on behalf of customers. This document presents a discussion of the suitability of the most relevant works, highlighting those that are most promising, and identifying the issues that are still necessary to reinforce in future research.

1. Introduction

Facing the growing energy demand, the exhaustion of fossil fuels, and the effect of greenhouse gases requires moving towards a new model of electrical grid. Aware of this situation, the US and Europe's governments [1–3] work on the development of the *Smart Grid*, which is defined as a more reactive, distributed and participative grid [4]. Its key goals include giving a prominent role to users' preferences, thus increasing the capacity to modulate demand, and using available power generation dynamically, features that facilitate the integration of renewable energy sources safely and efficiently. However, the fact that the electrical grid has not changed substantially over the past 60 years, along with the dependence of developed countries on the energy supply, suggests undertaking a gradual transition that protects the security and reliability of the system.

With the aim of smoothing this transformation process, many efforts are being devoted to the creation of autonomous local areas in the grid [5–7]. These areas, also known as *Distributed Electricity Networks* (DEN), are conceived as a self-controlled enclosed cell of the distribution network composed of Distributed Energy Resources (DER), dispatchable loads and storage systems, microgrids being one of the most representative examples. DENs make it possible that distributed generation can co-exist with traditional infrastructures and standard control systems. In the medium term, the aim of this transitional model is to build a grid composed of many linked self-controlled DENs capable of exchanging energy between themselves, satisfying significant parts of energy demand. Fulfilling the mission of acting as a cutting edge to the Smart Grid, the *Energy Management System* (EMS) of these enclosed areas has been proposed in numerous studies in form of micro-electricity market in which producers and consumers pursue network balance by exchanging energy blocks and modulating their production and consumption dynamically [8–13]. The novelty of this approach, which is known as *Supply and Demand Matching* (SDM), is that, unlike demand side management, autonomous distributed producers can actively participate in the management system. As the state of the art reveals [14], software agents are considered a

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suitable technology for carrying out this type of secondary control system, since they are entities capable of providing autonomous, distributed, reactive and intelligent behaviors.

The aim of this document is to review the agent-based methodologies that have been proposed for implementing the SDM management model. Principally, techniques coming from e-commerce and multiagent systems are studied, providing an understanding of their suitability, advantages and weaknesses. The document identifies and discusses the most promising lines of work and, after considering the needs and characteristics of the context, it concludes by pointing out the areas that need to be reinforced in future research. Furthermore, for a better understanding of the environment under study, this document provides an introductory section devoted to describing both the SDM model and the characteristics that a micro-electricity market must fulfill to work as an effective and fully operative management system. This preliminary study is particularly important because, as will be shown during the review of the state of the art, some features of electricity markets are frequently omitted with the result that the problem is not usually tackled in all its complexity.

The remainder of this article is organized as follows. Section 2 describes the challenges of management systems based on the SDM model, including the characteristics required by distributed electricity markets. Section 3 describes how approaches coming from e-commerce and artificial intelligence are applied in order to implement distributed energy management systems based on the SDM model. Section 4 discusses suitability and applicability of solutions. Section 5 is the conclusion.

2. Distributed electricity networks

2.1. Supply and Demand Matching management model

In electricity networks, the EMS is a subsystem intended to optimize the operation and energy cost by planning, coordinating and monitoring the activity of the units [15,16]. This works in the secondary control area drawing up plans in the short- and medium-term based on factors such as: conditions imposed by the main grid, specific features of supply devices, amount of load that can be modulated and shed, amount of energy that can be stored, electricity prices, current legislation, demand estimates and weather forecasts. Note that the EMS does not necessarily imply the presence of a physical device: this is primarily a concept that may be implemented using the simplest method, such as the hand-control, or the most modern and sophisticated ones, such as distributed systems based on software agents and recent advances in ICT. In practice, the EMS is mostly implemented as a central module based on nonlinear optimization algorithms [17,18]. However, this approach is considered neither efficient nor scalable for medium to large DENs because:

i. The computational cost of finding a solution increases exponentially with the size of the model, so that it can easily result in a NP-Hard problem [19].
ii. Stochastic and nonlinear variables typical of energy devices are difficult to model, so they have to be simplified or omitted.
iii. Any change in the configuration of the environment, or in the plans and characteristics of the units, requires restarting the optimization process, thus affecting to the reactivity and flexibility of the solution.
iv. The system provides a low level of autonomy to users, who are limited to expressing their intentions through prices or utility functions.

Even though there are also works based on neural networks [20] and fuzzy logic [21,22], centralized approaches do not provide autonomy and flexibility to the users. For those environments that require these features (which are usually typical of the Smart Grid), distributed control solutions are more suitable. In this line of thought, in the context of DENs, the EU CRISP project puts forward the *Supply and Demand Matching* (SDM) management model [8], whereby entities owning generation and consumption resources are enabled to dynamically bargain exchanges of energy blocks. The SDM model stands out for providing autonomy to producers, unlike techniques such as DSM (Demand Side Management) and DRR (Demand Response Resources), in which only authority nodes and consumers have capacity to act. In essence, the SDM model proposes the creation of micro-electricity markets in DENs. On a smaller scale, they emulate the mechanics of wholesale energy markets: through negotiations each node decides the amount of energy it produces and consumes, and for how long the action is carried out. Micro-electricity markets are conceived as being highly reactive, instantiated on demand, and with a short time horizon (usually shorter than 15 min).

The SDM model, as well as many other solutions related to the Smart Grid, require placing an autonomous piece of software at each node, which has the mission of: (i) representing the interests of users in micro-electricity markets; and (ii) coordinating with other nodes in order to meet collective goals. Intelligent agents, as evidenced by the literature, are seen as a suitable technology to address this challenge. In particular, intelligent agents are autonomous entities capable of developing flexible action planning in a certain environment to achieve well defined goals [23]. They are commonly characterized by showing skills such as goal orientation, autonomy, communication with other agents, capacity to react to external stimulus (reactivity) and make plans (proactiveness). Thus, the EMS, when implemented in a distributed manner, is a multiagent system in which software agents, representing local nodes, interact and coordinate between them in order to balance the system and accomplish both particular and collective goals. In particular, the autonomy of software agents enables the complete automation of users' participation, which is necessary in reactive and continuous operating systems such as the EMS. Specifically, it is expected that users' participation will be limited to providing basic directives to the software agents from time to time, such as the minimum profit they are willing to accept for selling their production, or the maximum price they are willing to pay for acquiring energy in specific situations.

2.2. General control architecture

In practice, the EMS is planned to be part of a hierarchical control architecture with three levels [24,25] (Fig. 1):

1. *Distribution Network Operator (DNO)*: The DNO is a management system in charge of the operation of the medium or low voltage area that the DEN is connected to. Thus, the area of action of the DNO can span multiple DENs.
2. *DEN Central Controller (CC)*: After receiving information from the DNO, as well as from internal sensors and components, the CC develops action plans and sends commands to the controllable units. This controller is therefore in charge of the internal operation of the DEN. If the DEN's management system is implemented using distributed techniques, such as the market-based methodologies studied in this work, the role of CC is limited to supervising the plans agreed by independent software agents representing the local controllers.
3. *Local Controller*: Each controllable unit of the DEN is associated with a LC. In centralized operation, the LC receives the set points