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Multi-agent based modeling for electric vehicle integration in a distribution network operation

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ABSTRACT

The purpose of this paper is to present a multi-agent based modeling technology for simulating and operating a hierarchical energy management of a power distribution system with focus on EVs integration. The proposed multi-agent system consists of four types of agents: i) Distribution system operator (DSO) technical agent and ii) DSO market agents that both belong to the top layer of the hierarchy and their roles are to manage the distribution network by avoiding grid congestions and using congestion prices to coordinate the energy scheduled; iii) Electric vehicle virtual power plant agents are in the middle level of the hierarchy and their roles are to manage the charge process of the electric vehicles; iv) Electric vehicle agents are placed at the bottom layer of the hierarchy and they represent electric vehicle owners with different users' profiles. To demonstrate the coordination behavior of the proposed system, a multi-agent simulation platform is developed based on the co-simulation environment of JACK, Matlab and GAMS. The aim of the multi-agent system is to simulate the collaborative (all agents contribute to achieve an optimized global performance) but also competitive environment (each agent will try to increase its utilities or reduce its costs).

1. Introduction

1.1. Background

Electric vehicles are important means to reduce the greenhouse gas (GHG) emission in the transport sector. Furthermore, electric vehicles can be used to balance intermittent renewable energy resources [1–3] in a smart grid. The double benefits explain the growing interests in electric vehicles. In the end of 2012 more than 180,000 electric vehicles (EVs) were sold worldwide and a total number of 20 million EVs are expected on the road in 2020 [4]. In addition, other distributed energy resources like heat pumps, energy storage, photovoltaic units, and combined heat and power plants are also important means used by the smart grid to reduce the GHG emission.

However, the integration of a high number of EVs and other distributed energy resources in the electric power system will require a significant grid capacity increase [5]. For example, uncontrolled charging of EVs can create new power demand peaks during the day, increasing power losses, voltage deviations and network congestion [6]. The increasing penetration of photovoltaic units introduces voltage rise problems [7]. Typically, the problems in the power distribution network caused by increasing electricity consumption from EVs, heat pumps and increasing penetration of distributed generation are solved by expanding the grid to match the size and the pattern of demand. Alternatively, in smart grids, the grid capacity problem can also be solved using advanced control strategies supported by an increased use of information and communication technology.

The advanced control strategies proposed in the literature for distributed energy resources integration include two main approaches: i) centralized control [8–10] and ii) market-based control [11,12]. Centralized control means the up-level controller directly schedule and control the low-level units to execute the command. Market-based control typically includes the features found in a market such as decentralized decision-making and interacting agent. In particular, to sum up the proposed control strategies for integrating electric vehicles, virtual power plant (EV VPP) is a widely advocated entity that aims to aggregate EVs and provide multiple services of EVs to power system operators. An EV VPP could be independent or integrated in an existing business function of the energy supplier. The EV VPP needs to guarantee driving needs of the EV owners as well as to take into consideration power systems requirements and constraints in its operation. EV

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VPP can implement centralized control/market-based control methods to maximize business values and to optimize the EVs charging and discharging processes [13,14]. A multi-agent system (MAS) based technology is very suitable to implement and assess different control strategies proposed in the grid capacity-allocation problem considering electric vehicle integration [15].

1.2. Literature review

MAS concept has been widely proposed for the applications in power systems, such as power system restoration, power system operation and control. The MAS applications in power systems can, in general, be divided into two types: 1) solving large-scale power system problems by distributing it locally and therefore reducing computational time [16,17]; 2) controlling power systems by distributing decision making to multiple levels in order to release the operational burden of a centralize controller [18,19]. Recently, many efforts have been published on using MAS for integrating distributed energy resources [20–24] into distribution networks. The studies are made from different perspectives such as controlling active demand on the residential side for provision of demand response services [25], integration of distributed generation [22], scheduling of integrated microgrids [26], or controlling virtual power plant emissions [27].

In particular, the multi-agent based modeling technology has been applied for management of distribution grid capacity with a large penetration of electric vehicles [19,28–31]. The agent-based control systems are adopted because of their efficiency to manage the complexity of a large systems such as future power distribution system [32,33]. In [19], Karfopoulos and Hatziargyriou proposed a distributed, multi-agent electric vehicle charging control method based on Nash certainty equivalence principle that considers distribution network constraints. Five types of agents are included in study. The results indicate that the proposed approach allocates electric vehicle charging power efficiently during off-peak hours, achieves valley filling and leads to maximization of load factor and minimization of energy losses. Miranda et al. [28] used MAS to design a distributed, modular, coordinated and collaborative intelligent charging network which schedules the charging of up to fifty electric vehicles as well as eliminating grid overloading. The study considers the allocation of electrical power among the multiple charging point agents by the power manager agent using an auction mechanism. Each charging point (CP) agent makes a bid of the charging power for the next 15 min and sends it to the power manager agent until the CP get the desired state of charge of the battery, then the local power manager agent sorts out the orders to determine which electric vehicle can be charged during the time slot. Papadopoulos et al. [29,30] proposed an agent-based control system to manage the charging of electric vehicles at times of low electricity price as well as adhering to the distribution network technical constraints. The two studies [29,30] are performed from scheduling and real time control perspectives. The laboratory results validated the effectiveness of the proposed solutions. In [31], multi-agent based technology is applied for distribution grid congestion management considering the integration of electric vehicles.

In general, studies [19,28–31] used an agent-based distributed decision-making model to incorporate market mechanisms to allocate grid capacity. The results indicated that the agent-based distributed decision-making mechanisms solve the grid congestion efficiently. However, the use of multi-agent based technology for solving voltage band violations because of electric vehicles still need investigations in the literature.

Besides, much work on simulations need to be developed, as discussed in [34]. Currently available software tools provide either modeling of dynamic electric power networks or implementation of intelligent system techniques such as intelligent agents. Therefore, a software platform that can simulate multi-agents based control strategies that incorporates power system dynamics and intelligent control strategies is required. For example, a Java Agent Development Framework (JADE) is used to develop the multi-agent system in [19], however, it is not mentioned what kinds of tools are used for power system dynamics calculation and decision making. In [28], Matlab is used for emulating an agent-based application and thus it cannot explicitly model the typical MAS entities such as agent, plan and event. In [29,30], JADE is used for the MAS development and a load flow software and artificial neural network technique are used for DSO agent's decision making. However, the load flow software is not explicitly described in the study, the test network of Tecnalia's Laboratory mentioned in the study cannot be easily generalized. In [31], JACK and Matlab is used for multi-agent system development, however, power flow calculation is not included that cannot support a power system operation for voltage problem solving.

1.3. Aim and contributions

The present paper aims to develop an agent-based control system for simulating and operating future distribution networks characterized by high penetration of demand side resources. The objectives of the agent-based control system are to prevent grid congestion problems and voltage-band violations. In particular, electric vehicles are used in this study to demonstrate the proposed agent-based control system.

There are two main contributions of this study: 1) a hierarchical multi-agent system is proposed and developed for the power management of future power distribution systems considering electric vehicle integration and operational constraints of the distribution network including power transformer/cables congestion and buses voltage band violation. 2) The developed multi-agent system presents a unique simulation platform based on the software integration of JACK, MATLAB and GAMS. The platform can integrate the advanced optimization algorithms/power flow calculations required by the actors and the negotiations between the interacting agents in a collaborative but also competitive environment.

In the developed agent-based control system, each EV VPP agent can manage the EVs' charge considering the energy prices and the EV agent's requirements (schedule trips, batteries technical limits, etc.). Before biding the energy schedule into the electricity spot market, a prior interaction between EV VPP agents and distribution system operator technical agent (DSO Tech agent) is required. The energy schedule of EV VPP agent is sent to DSO Tech agent and DSO Tech agent evaluates the overall network performance considering the network technical constraints, namely the bus voltage magnitude and the line thermal limits. If congestion exists, the distribution system operator market agent (DSO market agent) uses a market-based control method [35] to coordinate the energy schedule of EV VPP agents.

To facilitate the understanding of the state of the art review and to clarify the contributions of this study, Fig. 1 is presented in this study.

1.4. Paper organization

The present paper is organized as follows: after this introductory section, Section 2 describes the proposed multi-agent system and the operation of the agents. Section 3 describes the implemented multi-agents platform. In Section 4, simulations are shown