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Demand side integration in LV smart grids with multi-agent control system

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ABSTRACT

The *low-carbon* society requires significant changes in the operation and planning of distribution systems. In order to exploit existing low voltage systems, Demand Side Integration is essential for offering services that increase security and quality of supply, improve energy efficiency and reduce the energy cost. In this paper, a decentralised multi-agent system (MAS) for the coordination of active demand and plug-in electric vehicles is proposed. The load Aggregator aggregates the demand to sellenergy and services by operating a Master Agent and independent Agents. The Master Agent coordinates independent Agents for moving demand to the most convenient hours without degrading power quality. All Agents use a combination of local and global data to perform the optimisation following the Nash's theory on games. The MAS does not require huge bidirectional information flows and is better suited than centralised systems to LV systems.

1. Introduction

Low voltage (LV) systems started experiencing the burden of new consumption profiles characterised by high coincidence factors (e.g., domestic electric vehicles recharge systems), new high efficiency domestic appliances (e.g., heat pumps, induction cooking systems), and the impact of small generation (e.g., photovoltaic, CHP and small wind generators). Distribution System Operators (DSO) generally had not seriously taken LV systems into account in the planning process as a consequence LV systems are not ready for the transition toward the *low-carbon* society, which requires significant changes in the operation and planning of distribution systems [1]. Particularly, in order to exploit existing LV assets (i.e., secondary substations, transformers, and circuits) without limiting the usage of electric energy and the activation of new markets open to final consumers, the resort to Demand Side Integration (DSI) policies with the direct control of customers is becoming more and more necessary. The concept of active demand (AD), introduced in the context of the European project ADDRESS is based on the idea that end users should play an active role in the electricity distribution process, adjusting their consumption patterns depending on the dynamics of the energy markets [2,3]. The demand elasticity offered by end-users allows deferring the reinforcement of the existing grid infrastructures caused by new load profiles and distributed generation. DSI provides the means to modify the consumer's load to meet the network constraints. These load profile modifications can spontaneously be implemented by the end users themselves, typically driven by price signals, or be managed by an entity, called Aggregator, which is entrusted by the end users to change their consumption habits according to its needs (i.e., remote management (RM)) [1]. The RM can be obtained with centralised systems that in LV applications require complex communication system with high bandwidth usage. The RM can also be realised with hierarchical/decentralised systems characterised by reduced communication between the Aggregator and the customers with most of decisions made at customers level. Multi-agent system (MAS) with two or more intelligent agents that by pursuing local individual goals allow reaching a system goal can be successfully used for RM without complex centralised control systems. MASs have been used in monitoring and diagnostics, distributed control, modelling and simulation, and protection of power system [4] and are suited for the operation of LV systems with distributed energy resources (DER). In Ref. [5] MAS is used to optimally schedule EV charging, to fill the valleys in electric load profiles, but without providing other services to the network. In Ref. [6] two classes of EV charging coordination (the first based on classical quadratic programming and the second on market-based MAS), with the aim to reduce the peak load and the load variability in a distribution grid, are presented. Despite the comparison is based on power quality analysis the voltage profile is not optimised by the MAS. A

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MATLAB/JAVE/JADE MAS architecture for smart home energy management is proposed in Ref. [7] that takes into account customers' preferences and offers services to the distribution system. In Ref. [8] a MATLAB MAS for the DER management is developed; ZEUS is used to facilitate agent communications and allow negotiations for power exchange. The MAS uses a hierarchy of agents at different layers: a load management system, which is the decision maker agent, a zone agent that has the information about distributed generators (DG) and controllable loads available in its zone, a load agent that has the information for all controllable load and DG agents that have information about the DG.

The MAS proposed in the paper improves the MAS application for the control of LV networks with active loads and EV; the main contribution is represented by the modification of MAS algorithms for the RM of loads and EV (according to ADDRESS models) without a centralised optimisation system as well as the definition of network constraints that allow following specific DSO requests. With the RM the Aggregator is able to change the behaviour of customers in the portfolio (e.g., charging of batteries, change of the end-users' consumption patterns) [9]. In this paper, the Aggregator coordinates the behaviour of independent agents so that the total load demand (EVs and loads) does not cause system issues (i.e., not exceeding a defined voltage limit or the cable rated capacity). The structure of the paper is as follows. Section 2 describes MAS and the realisation proposed by the authors. Section 3 describes the structure and implementation of the MAS direct control for DSI. In Section 4 a case study to analyse the MAS behaviour is proposed. Section 5 is devoted to the discussion of results and, finally, Section 6 reports some concluding remarks.

2. MAS for Demand Side Integration

DSI policies involve the participation of demand in several ways; one of them is the RM of loads. The demand RM with an intermediate player, the Aggregator, allows DSO to reduce the impact on the systems of loads with high coincidence factor (e.g., EV) and of not dispatchable small generation. At LV level, decentralised control systems have the merit to allow the operation of many small customers with a reduced information flow by exploiting data from intelligent metering [10,11]. MAS realise decentralised control systems with a Master–Slave interaction that allows finding a global optimum without a direct control of each resource. The general structure of the control is based on autonomous agents that exchange information about the state of the system to develop strategies that enable the achievement of both local targets and global objectives. In the proposed MAS control system, the Agents responsible for the EV charging stations and the AD communicate directly with the Master Agent (MA), through a vertical communication. No information is exchanged among the agents in the current release (EV charging station and AD).

The MA broadcasts the data necessary for Agents' local optimisations, gathers the results from local agents, and commands new local optimisations until a stable and optimal solution is achieved. In order to achieve an optimal DSI strategy by offering services like voltage regulation, each agent looks for the minimum of an Objective Function (OF) that is based on local information and on the average behaviour of the other agents in the system. In other words, each Agent tries to maximise its benefits but in doing so it is limited by the other Agents that are looking for the same maximisation. This concept has been introduced in Ref. [12] for reducing the risk of dummy charging of EV during the peak hours, and improved in Ref. [13] with the MAS methodology enriched by a direct control of voltage profiles in LV networks. The main novelty of the present paper is that the MAS control system has been improved to include DSI RM.

2.1. Optimisation problem

The optimisation of MAS is performed with a weakly coupled game approach. Agents know their own dynamics (i.e., maximum availability rate for the increase/reduction of load), the energy price and the average state of all other agents ("mass" behaviour). Therefore, each agent optimises an OF using local information about its state and global information, i.e., the pricing strategy, the average behaviour of the other agents and the technical constraints [14]. The DSI strategy is based on the virtual cost, $p(t, P_t)$, expressed by (1) [14]. The virtual cost is a linear function of the ratio between the total demand and the nominal power of the MV/LV transformer. Eq. (1) shows that the highest virtual prices are expected at peak hours [12,13]. In this paper the virtual price has been modified to explicitly include the role of AD and EV

$$p(t, P_t) = f\left(\frac{D(t) + \sum_{N}^{i=1}(P_{EV,i}(t) + P_{AD,i}(t))}{P_{tr}}\right) \quad (1)$$

$$P_t(t) = \sum_{i=1}^{N} P_i(t) = \sum_{i=1}^{N}(P_{EV,i}(t) + P_{AD,i}(t)) \quad (2)$$

where:

- $D(t)$ is the forecasted non-EV demand of the MV/LV transformer at time t [kW];
- $P_{EV,i}(t)$ is the i-th EV charging power at time t [kW];
- $P_{AD,i}(t)$ is the i-th AD contribution (power reduction/increase) at time t [kW];
- $P_i(t)$ is the sum of the i-th EV charging power at time t and the i-th AD contribution (power reduction/increase) at time t [kW];
- P_t includes the total charging power of the EVs and the global AD contributions at time t [kW];
- P_{tr} is the nominal power of the MV/LV transformer [kW];
- t is the time interval (step of 1 h);
- N is the effective number of Agents participating to the MAS control. It is the sum of the EVs involved in the charging control system and the loads included in the AD programs.

The calculation of (1) and (2) is performed by the MA that sends the value of the virtual cost $p(t, P_t)$ and $P_t(t)$ to Agents that execute the mono-dimensional constrained optimisations expressed by (3). Eq. (3) is formed by two terms [14]. The first term is the virtual cost for purchasing energy from the system; the smaller is this cost the bigger is the distance from the peak hours. The second term takes into account the deviations between the Agent behaviour and mass behaviour of all Agents; this term avoids the risk that all Agents by moving far from the peak will form a new undesired peak in another hour. Indeed, each Agent tries to maximise its own benefits but the deviation from the mean behaviour is a cost that guides the global optimisation to a real global (system) minimum

$$\min J_i(P_i, P_{-i}) = \sum_{t=0}^{T-1} \left\{ p(t, P_t) \cdot P_i(t) + \delta[P_i(t) - \mathrm{avg}(P_t)]^2 \right\} \quad (3)$$

subject to Agent specific technical constraints

$$\mathrm{avg}(P_t) = \frac{1}{N}\sum_{i=1}^{N} P_i(t) \quad (4)$$

where P_i denotes the i-th agent power, P_{-i} the power of other agents (excluding i-th agent), $\mathrm{avg}(P_t)$ is the average of the power controlled by Agents, t is the time at the beginning of each interval (step of 1 h), T is the final time of the period (i.e., 0:00 a.m.) and δ is a tracking parameter with non-negative constant value [13]. The technical