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A distributed demand-side management framework for the smart grid

Antimo Barbato [a], Antonio Capone [a,*], Lin Chen [b], Fabio Martignon [b,c], Stefano Paris [d]

[a] DEIB, Politecnico di Milano, via Ponzio 34/5, 20133 Milano, Italy
[b] LRI, Paris-Sud University, Bat. 650, rue Noetzlin, 91405 Orsay, France
[c] IUF, Institut Universitaire de France, France
[d] LIPADE, Paris Descartes University, 45 rue des Saints Peres, 75270 Paris, France

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ABSTRACT

This paper proposes a fully distributed Demand-Side Management system for Smart Grid infrastructures, especially tailored to reduce the peak demand of residential users. In particular, we use a *dynamic pricing strategy*, where energy tariffs are function of the overall power demand of customers. We consider two practical cases: (1) a fully distributed approach, where each appliance decides *autonomously* its own scheduling, and (2) a hybrid approach, where each user must schedule all his appliances. We analyze numerically these two approaches, showing that they are characterized practically by the same performance level in all the considered grid scenarios.

We model the proposed system using a non-cooperative game theoretical approach, and demonstrate that our game is a generalized ordinal potential one under general conditions. Furthermore, we propose a simple yet effective best response strategy that is proved to converge in a few steps to a pure Nash Equilibrium, thus demonstrating the robustness of the power scheduling plan obtained without any central coordination of the operator or the customers. Numerical results, obtained using real load profiles and appliance models, show that the system-wide peak absorption achieved in a completely distributed fashion can be reduced up to 55%, thus decreasing the capital expenditure (CAPEX) necessary to meet the growing energy demand.

1. Introduction

The electricity generation, distribution and consumption are in the throes of change due to significant regulatory, societal and environmental developments, as well as technological progress. Recent years have witnessed the redefinition of the power grid in order to tackle the new challenges that have emerged in electric systems. One of the most relevant challenges associated with the current power grid is represented by the *peaks* in the power demand due to the high correlation among energy demands of customers. Since electricity grids have little capacity to store energy, power demand and supply must balance at all times; as a consequence, energy plants capacity has to be sized to match the total demand peaks, driving a major increase of the infrastructure cost, which remains underutilized during off-peak hours. This waste of resources has become an even more critical issue in the last few years due to the increase of the worldwide energy consumption [1] and the increasing share of renewable energy sources [2]. High energy peaks are mostly due to residential users, who cover a relevant portion of the worldwide energy demands [3], but are inelastic with respect to the grid requirements as they usually run their home appliances only depending on their own requirements. For this reason, residential users can play a key role in addressing the peak demand problem. Time-Of-Use (TOU) tariffs represent a clear attempt to incite users to shift their energy loads out of the peak hours [4].

The most promising solution to tackle the peak demand challenge is represented by the Smart Grid, in which an intelligent infrastructure based on Information and Communication Technology (ICT) tools is deployed alongside with the distribution network, which can deal with all the decision variables while minimizing the effort required to end-users. All data provided by the grid, such as the consumption of buildings [5,6], electricity costs and distributed Renewable Energy Sources (RESs) data, can be used to optimize its efficiency through *Demand-Side Management* (DSM) methods, which represent a proactive approach to manage the household electric devices by integrating customers' needs and requirements with the retailers' goals [7]. The main objective of these methods is to shape the consumers' energy

* Corresponding author. Tel.: +39 02 2399 3449; fax: +39 02 2399 3413.
E-mail addresses: antimo.barbato@polimi.it (A. Barbato), antonio.capone@polimi.it (A. Capone), lin.chen@lri.fr (L. Chen), fabio.martignon@lri.fr (F. Martignon), stefano.paris@parisdescartes.fr (S. Paris).

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demand in a proper way by deciding *when* and *how* to execute home appliances so as to improve the overall system efficiency while guaranteeing low costs and high comfort to users.

The most common way to incentivize consumers to modify their consumption is to define convenient electric energy tariffs. In fact, by increasing the energy price, we expect that users' demand naturally tends to decrease (i.e., higher prices cause consumption to decrease, and *vice versa*). A considerable number of tariffs are available to define electric energy prices among which time-of-use, Critical-Peak Pricing (CPP) and Real-Time Pricing (RTP). In the TOU case, electricity prices depend on the time of day and are set in advance. Critical-peak pricing is a variant of TOU, in which in case of emergency situations (e.g., high demand) the price is raised. Finally, in real-time pricing, electricity prices can change as often as hourly, reflecting the utility cost of supplying energy to consumers. All these tariffs can be defined to achieve different purposes, such as reducing the peak load and maximizing the usage of renewable energy generation. In the first case, the energy prices are higher during peak hours and lower in off-peak hours. As a consequence, consumers are incentivized to move their loads to off-peak periods, therefore reducing the peak load, and the need for generation, transmission and distribution capacity, as well as grids investments. In the second case, the electricity prices are higher in case of lack of renewable generation and lower in case of excess of Renewable Energy Resource (RES) productions, in order to elastically adapt the users' demand to fluctuating generations of renewable sources.

In this paper we propose a novel, *fully distributed DSM system* aimed at reducing the peak demand of a group of residential users (e.g., a smart city neighborhood). In particular, we consider a *real-time pricing scheme*, where energy tariffs are function of the overall power demand of customers.

We model our system using a game theoretical approach, considering two practical cases where (1) each appliance decides *autonomously* its scheduling in a fully distributed fashion (Single-Appliance DSM), and (2) each user must schedule all his home appliances (Multiple-Appliance DSM). The proposed approach automatically ensures the reduction of the electricity demand at peak hours due to dynamic pricing.

We compare numerically these two cases, showing that the first is characterized only by a negligible performance degradation in all the considered grid scenarios. Nevertheless, while both mechanisms achieve almost the same performance level, the Multiple-Appliance DSM system requires a more complex architecture with a central server for each house that collects all appliances information and plays on behalf of the householder. Such an approach would increase the installation and operating costs due to the higher system complexity. On the contrary, in the Single-Appliance DSM system, one can use the processing and communication capabilities of devices that can autonomously optimize their usage, thus greatly simplifying the architecture design and system configuration. This solution is made possible by the diffusion of *Smart Appliances* that are no longer merely passive devices, but active participants in the power grid infrastructure [8].

We underline that, while recent literature has focused on the design of DSM systems for *controllable* devices [9], namely devices whose power load profile within their operating time can be modulated according to the DSM goals, our work designs a distributed DSM to select the best (cheapest) schedule for *shiftable* appliances. Indeed, differently from air conditioning or heating systems, appliances like washing machines and electric dishwashers have a fixed power profile optimized for specific goals. In such cases, a user can choose only the starting time for each shiftable appliance, whose power profile is fixed. Nonetheless, the decision on the appliance's starting time affects the price paid in all successive execution time slots, since the appliance's operational phases cannot be postponed or modified. Therefore, our scheme is complementary to approaches devised for controllable devices like the one presented in [9], which solve an orthogonal distributed power scheduling problem.

We demonstrate that our game is a *generalized ordinal potential game* [10] under some simple and very general conditions (viz., the regularity of the pricing function). Such feature guarantees some nice properties, such as the existence of at least one pure Nash equilibrium (where no player has an incentive to deviate unilaterally from the scheduling pattern he decided upon). Furthermore, we show that any sequence of asynchronous improvement steps is finite and always converges to a pure Nash equilibrium.

In summary, our paper makes the following contributions:

- The proposition of a novel, fully distributed DSM method, able to reduce the peak demand of a group of residential users, which we model and study using a game theoretical framework. In our vision, the energy retailer fixes the energy price dynamically, based on the total power demand of customers; then, appliances autonomously decide their schedule, reaching an efficient Nash equilibrium point.
- Mathematical proofs that our proposed game is a *generalized ordinal potential game*, under general conditions.
- The demonstration of the Finite Improvement Property, according to which any sequence of asynchronous improvement steps (and, in particular, *best response dynamics*) converges to a pure Nash equilibrium.
- A thorough numerical evaluation that shows the effectiveness of the proposed approach in several scenarios, with real electric appliances scheduled by householders.

The paper is organized as follows. Section 2 discusses related work. Section 3 describes the main characteristics of the distributed system we propose to manage the energy consumption of residential users. Section 4 presents our proposed game theoretical formulation for the Single and Multiple-Appliance DSM, as well as the structural properties of our game. Numerical results are presented and analyzed in Section 5. Finally, Section 6 concludes the paper.

2. Related work

Demand-Side Management (DSM) mechanisms have recently gained attention by the scientific community due to their advantages in terms of wise use of energy and cost reduction [11]. In DSM systems proposed in the literature, a mechanism is defined that, based on energy tariffs and data forecasts for future periods (e.g., photovoltaic power generation, devices future usage), is able to automatically and optimally schedule the home devices activities for future periods and to define the whole energy plan of users (i.e., when to buy and sell energy to the grid) [12]. The main goal of these solutions is to minimize the electricity costs while guaranteeing the users' comfort; this can be achieved through the execution of methods based on optimization models [13,14] or heuristics, such as Genetic Algorithms [15] and customized Evolutionary Algorithms [16], which are used to solve more complex formulations of the demand management problem. Since RESs diffusion is rapidly increasing, several works include renewable plants into DSM frameworks. In these cases, devices are scheduled also based on the availability of an intermittent electricity source (e.g., PV plants) and users' profits from selling renewable electricity to the energy market are taken into account [17]. The uncertainty of RESs generation forecasts is tackled through stochastic approaches, such as stochastic dynamic programming which is a