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Reputation-based joint scheduling of households appliances and storage in a microgrid with a shared battery

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ABSTRACT

Due to the decreasing revenues from the surplus renewable energy injected into the grid, mechanisms promoting self-consumption of this energy are becoming increasingly important. Demand response (DR) and local storage are among the widely used mechanisms for reaching higher self-consumption levels. Deploying a shared storage unit in a residential microgrid is an alternative scenario that allows households to store their surplus renewable energy for a later use. However, this creates some challenges in managing the battery and the available energy resource in a fair way. In this paper, a reputation-based centralized energy management system (EMS) is proposed to deal with these issues by considering households' reputations in the reallocation of available energy in the shared storage unit. This framework is used in an optimization problem, in which the EMS jointly schedules households' appliances power consumption and the energy that each household can receive from the storage unit. The scheduling problem is formulated as a Mixed Integer Linear Programming (MILP) with the objective of minimizing the amount and price of energy absorbed from the main grid. The MILP problem is coded in GAMS and solved using CPLEX. Numerical analysis is conducted using real data of renewable energy production and appliances' demand profiles for different classes of households and different annual periods in Spain. Simulation results of the different scenarios show that by using the proposed framework higher cost savings can be achieved, in comparison with the classical scheduling scenario. The saving can reach up to 68% when different classes of households exist in the microgrid. The results also show that the fairness in energy allocation is guaranteed by the reputation-based policy, and that the total power absorbed from the main grid by the whole microgrid is significantly decreased.

1. Introduction

Microgrids are typically conceived as integrated operational and technological small-scale systems that help in optimizing power generation, distribution, and consumption. The concept refers to a set of loads (e.g., households), Distributed Generation (DG) (e.g., small-scale on-site Renewable Energy Sources (RESs)), and possibly energy storage systems (ESSs) (e.g., batteries), operating as a single controllable system that provides power to its local area [1,2].

Since a large portion of electricity is consumed in the residential sector, involving citizens in the efficient planning and use of electricity is key. For instance, a 25% of the total electricity consumption in Spain is in the residential sector. Moreover, the share of electricity used by appliances and electronics in an average household accounts for around two-thirds of its total electricity consumption [3]. Hence, the management of households' appliances power consumption can play an important role in saving costs and reducing the environmental impact of the electricity consumed in the residential sector.

Accordingly, demand response (DR) programs have been defined, providing several economic and technical benefits for utilities and consumers [4]. Namely, DR programs aim to reshape consumer energy profiles in order to improve the reliability and efficiency of the grid and defer generation capacity expansion [5,6]. Participants can take actions in response to a DR program by means

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of load management schemes such as demand limiting, demand shedding, demand shifting and on-site generation [4]. Recently, an increasing focus of DR is placed on the residential sector motivated by the vision of future homes with smart appliances that allow their control and integration in energy management systems (EMSs) [7]. DR can be performed as incentive-based or price-based programs [8]. Incentive-based schemes compensate participating users for demand reduction by offering discount rates separated to electricity prices [9]. Some examples of this kind of programs are Direct Load Control (DLC), interruptible/curtailable load, demand bidding and buyback, and emergency demand reduction [8]. Price-based schemes provide energy customers with time varying rates that define different electricity prices at different times. The customer reacts to the fluctuations in the electricity prices. This kind of programs might be confusing to customers, therefore scheduling techniques are needed to help customers manage their load [5]. Some of the implemented price-based schemes are Time of Use (ToU), Critical-Peak Price (CPP), and Real-Time Price (RTP) [8,10]. RTP in DR programs are usually based on day-ahead or real-time wholesale price [11].

In [12], the potential benefits of DR on a residential distribution network operation are studied and the results show its influence in the load and voltage profiles, the network losses, and the service reliability. Still, some of the challenge of using DR in the residential sector are to establish an optimal DR system strategy beneficial for both customers and the utility, schedule demand in order to balance energy consumption with the available supply and implement the communication system that handles the DR [5]. To deal with these issues, some research has been conducted. In [11], a dynamic DR controller is proposed to curtail peak load and save electricity under two RTP programs. The objective is to provide the set-point temperature for heating, ventilating and air conditioning (HVAC) systems based on the dynamic price of electricity and occupant preferences. In [13], two noncooperative games are defined to model a DR associated with the interaction among multiple utilities and customers in a smart grid. The first one, a supplier-side game, defines the utility companies' profit maximization problem. The utility companies submit bids, then the electricity price is computed and sent to the customers. In the second game, a customer-side game, the price anticipating customers determine optimal shiftable load profile to maximize their daily payoff. In [14], the DR program is modelled as a repeated game with RTP scheme from the utility company perspective. The goal is to achieve a desired value for the peak to average ratio (PAR) in the aggregate load demand, and at the same time benefit the customers, by reducing their long-term cost. Nevertheless, those approaches are focused on the aggregated load and they do not consider the simultaneous management of other distributed energy resources.

The management of households' appliances and distributed energy resources has received significant attention in the last few years [15–24]. In [15], the smart appliance power scheduling problem is modeled using Mixed Integer Linear Programming (MILP), capturing relevant appliance operational constraints. A distributed algorithm to schedule households' appliances aiming to minimize power costs by using game theory is presented in [16], where households are the players of the game and their strategies are the daily schedules of their appliances. In [17,18], an ESS is used in the appliance scheduling problem, in which the battery charges from the main grid during off-peak times, and feeds the load during peak times. In [19], a residential energy consumption scheduling of electrical and thermal appliances to minimize energy costs of a customer with a RES is proposed taking its comfort into consideration. An artificial intelligence based smart appliance scheduling approach for reducing energy demand in peak periods by maximizing the use of RES in the residential sector is proposed in [20]. Other EMS that consider the ownership of both an on-site RES and an ESS in each household have been considered in [21–24]. However, equipping each household with an on-site ESS might be economically unaffordable due to the high cost of batteries which are required to buffer sufficient renewable energy for an average household daily power consumption [25]. Besides, batteries with long lifespan have a big physical size that makes them difficult to be located inside houses [26].

On the other hand, the increasing costs of electricity from the grid, the decreasing cost of photovoltaics (PV) technology and the expected decreasing revenues from excess electricity injected into the grid in the near future will raise the incentives to maximize the self-consumption ratio [27–29]. Moreover, in some cases, like the current situation in Spain, the surplus PV electricity injected into the grid is not remunerated and thus is lost for the household [29]. Therefore, new operation frameworks are needed in order to optimize the benefit from on-site RESs.

In this study, we consider a microgrid composed of households each with a PV system that can inject the surplus PV energy into the main grid but without any compensation for it. To take advantage of this energy, a shared ESS is used (e.g., a battery), which is managed by a reputation-based EMS. The battery charges only from households surplus energy. In [30], a similar scenario is proposed with a more expensive electrical implementation and assuming the ESS as an inexhaustible energy resource that never gets fully charged or discharged. The reputation-based energy allocation policy is considered in the allocation of available energy in the shared battery, in a fair way, since they record the previous energy contribution of each household in charging the battery. This is more meaningful in a system where households' demands may exceed the available energy in the shared battery at some time periods. This framework is used in a daily appliances power scheduling optimization model, in which the EMS jointly schedules households appliances power consumption and the energy each household can receive from the shared battery, taking its operational constraints into account.

The contributions of this paper are summarized as follows:

- We propose a reputation function, according to which the EMS manages the available energy in the shared battery, and determines the portion of energy that will be scheduled to each household.
- We apply the proposed framework in a centralized optimization problem to minimize the energy absorbed from the grid in a DR scheme of RTP. The optimization model provides the power battery profiles as well as appliances power scheduling for each household.

The paper is structured as follows. The system model is presented in Section 2. The proposed reputation factor is described in Section 3. In Section 4, the household appliances power scheduling is presented and the centralized optimization problem is formulated in Section 5. Numerical results are discussed in Section 6. Finally, we conclude the paper and give pointers for possible future directions in Section 7.

2. System model

In this work we consider a generic microgrid which consists of a set of households $\mathcal{N}$, indexed by $i \in \{1, 2, \ldots, N\}$, with a small-scale on-site RES (e.g., a solar PV system). Households are connected to the main grid and to the battery via AC power lines. They share their surplus harvested renewable energy by storing it in the shared battery that is controlled by an EMS. The EMS, in turn, controls the microgrid, manages households' demands, and allocates the shared renewable energy to them following an energy allocation policy. Households are connected to the main grid to secure their power