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Matching supply with demand: A power control and real time pricing approach

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ABSTRACT

This paper proposes a novel power control and real time pricing approach to match supply with demand for smart grid. We formulate a utility optimization problem to maximize the comfort level of the consumer under a reasonable payment. Then, we develop a power control and pricing algorithm to search for the optimal power consumption and price and give a distributed implementation method. Simulation results show that the algorithm has rapid convergence speed and keeps the balance between electricity supply and demand with real time pricing.

1. Introduction

The energy demand in many countries is growing with the development of economy and society. In recent years, smart grid was proposed to meet the steadily increasing demand [1]. In smart grid, matching supply with demand can be implemented by unit commitment [2] and economic dispatch [3] with integration of demand response programs, which make consumers shift their loads away from peak times [4,5]. In fact, various pricing strategies have been proposed to implement demand response in smart grid, such as time of use (TOU), critical peak pricing (CPP), extreme day CPP (ED-CPP), extreme day pricing (EDP), and real time pricing (RTP) [6]. More recently, with the development of smart metering technologies, which will enable reliable, real-time, and two-way information exchange between consumers and electricity service providers, RTPs can be provided to consumers multiple times a day, hour, or even second. RTP programs have become direct and efficient demand response programs suitable for competitive electricity markets [6]. In the RTP program, the service provider announces electricity prices on a rolling basis. The price for a given time period, e.g., an hour, is determined and announced before the start of the period, e.g., 15 min beforehand.

To handle the two-way information exchange and decision making, the consumers will rely on energy management controllers (EMCs), which can modify power usage across a home or building based on electricity prices and consumer preferences. From the perspective of service provider, providing high frequency pricing updates will enable better load shaping and thus better matching between supply and demand. For consumers, RTP will provide new opportunities to lower the cost by making smart usage decisions.

There exist a large number of literature about control and scheduling strategies for demand response. Fuzzy-logic methods were applied to the power system optimization and control [7]. In [8,9], the major concern was reducing the total energy cost of service provider without considering the balance between supply and demand. To deal with this, the work in [10] proposed a RTP algorithm to match supply with demand by maximizing the social welfare. In general, the consumers in smart grid will not cooperate with each other to maximize the social welfare. The work in [11] gave time-varying prices that can align the individual optimality with the social welfare maximization. In that case, the social welfare can be implemented by optimizing the individual utility. Then, a distributed scheduling mechanism was presented to reduce the peak demand within a neighborhood of households [12]. Moreover, the game theory method was applied to the charging control for plugged-in hybrid electric vehicles [13]. An optimal strategy was proposed for a retailer with the consideration of medium and short-term decisions [14]. Nevertheless, few papers are

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devoted to the method of searching for the optimal scheduling strategy. Then, a question arises naturally: how consumers choose their power consumption distributively and how service provider sets the electricity price, such that the total load can meet the supply?

In this study, we propose a power control and real time pricing approach based on distributed optimization, which is suitable for analyzing the distributed strategy design problem. The main contributions are as follows.

- We formulate demand response as a utility optimization problem to maximize the profits of consumers.
- A distributed power control and RTP algorithm is developed with stability analysis.
- We give the implementations for the power control and RTP algorithm.

The rest of the paper is organized as follows. We describe the system model in Section 2 and formulate the demand response as a utility optimization problem in Section 3. Section 4 gives a distributed power control and RTP algorithm. The implementations are discussed in Section 5 and the simulation results are shown in Section 6. Finally, we draw conclusions in Section 7.

2. System model

As shown in Fig. 1, we consider a residential power system consisting of one service provider and N consumers. The service provider purchases electricity from the wholesale market and sells it to the consumers. We assume that each consumer installs an EMC to interact with the service provider through two-way communication networks and schedule the power usage among the smart appliances such as air conditioner.

The intended operation cycle is divided into K time slots. In each time slot k $(k \in \{1, 2, \ldots, K\})$, the service provider measures the power consumption of the consumers and publishes the electricity price. The set of consumers is denoted by $\mathbb{N} = \{1, 2, \ldots, N\}$ and the corresponding power consumption is defined as $\boldsymbol{x}^k = (x_1^k, \ldots, x_i^k, \ldots, x_N^k)$, where x_i^k is the power consumption of consumer i in time slot k. According to the technical report from U. S. Department of Energy [15], the electricity price is approximated to be a linear function of the total load.

$$C(\boldsymbol{x}^k) = a^k + b^k \sum_{i \in \mathbb{N}} x_i^k, \tag{1}$$

where a^k and b^k are positive parameters, which are decided by the service provider to implement elastic pricing. The pricing function (1) indicates that the electricity price is increasing with the total load of consumers. To describe the comfort level of consumers, a quadratic function with linear decreasing marginal benefit is given [16].

$$W_i(x_i^k, \omega_i^k) = \begin{cases} \omega_i^k x_i^k - \frac{\alpha}{2}\left(x_i^k\right)^2, & \text{if } 0 \leqslant x_i^k \leqslant \frac{\omega_i^k}{\alpha}, \\ \frac{\left(\omega_i^k\right)^2}{2\alpha}, & \text{if } x_i^k \geqslant \frac{\omega_i^k}{\alpha}, \end{cases} \tag{2}$$

where α is a positive coefficient and $\omega_i^k > 0$ is a predefined parameter, which varies across different time slots in a day. The quadratic comfort level function in (3) denotes that a consumer is willing to choose larger power consumption with ω_i^k/α as the saturation value.

Each consumer is willing to obtain larger comfort under a reasonable payment. Thus, the utility of consumer i is defined to be its comfort level in equivalent revenue format minus the payment to the service provider.

$$U_i(\boldsymbol{x}^k) = W_i(x_i^k, \omega_i^k) - C(\boldsymbol{x}^k) x_i^k. \tag{3}$$

In the following, we will omit the time slot index k for convenience.

3. Problem formulation

In smart grid, each consumer is actually selfish and tries to maximize its own utility, but not at the expense of the others. We formulate a utility optimization problem, in which each consumer aims to maximize its own utility $U_i(\boldsymbol{x})$ under the constraints $0 \leqslant x_i \leqslant \omega_i/\alpha$.

$$x_i^* = \arg\max_{x_i} U_i(\boldsymbol{x}), \quad i = 1, 2, \ldots, N. \tag{4}$$

Here, the utility function of consumer i is not only determined by its own strategy x_i, but also the strategies of the other consumers. Therefore, the optimal solution of optimization problem (4) is the solution of the following equations:

$$\frac{\partial U_i(\boldsymbol{x})}{\partial x_i} = 0, \quad i = 1, 2, \ldots, N, \tag{5}$$

where the first derivative of $U_i(\boldsymbol{x}^k)$ with respect to x_i is denoted by

$$\frac{\partial U_i(\boldsymbol{x})}{\partial x_i} = \omega_i - \alpha x_i - C(\boldsymbol{x}) - \frac{\partial C(\boldsymbol{x})}{\partial x_i} x_i. \tag{6}$$

Substituting the pricing function (1) into (6) and combining with (5), we have

$$\omega_i - \alpha x_i - a - b \sum_{i \in \mathbb{N}} x_i - b x_i = 0, \quad i = 1, 2, \ldots, N. \tag{7}$$

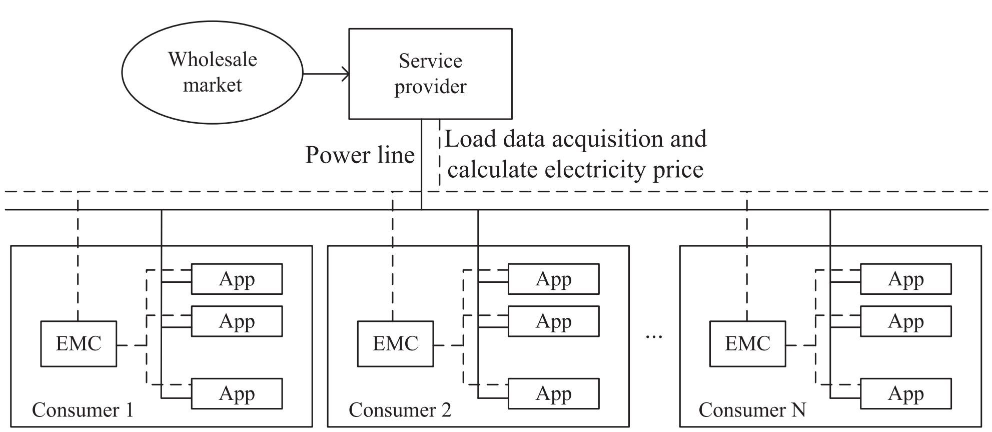

Fig. 1. A residential power system.