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A nonlinear control method for price-based demand response program in smart grid

Jie Yang [a,*], Guoshan Zhang [b], Kai Ma [a]

[a] School of Electrical Engineering, Yanshan University, Qinhuangdao, Hebei 066004, China
[b] School of Electrical Engineering and Automation, Tianjin University, Tianjin 300072, China

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ABSTRACT

This paper proposes a price-based demand response program by the nonlinear control method. The demand response program is formulated as a nonlinear power management system with price feedback. We give the conditions of the price parameters for both the global asymptotic stability of the system and the social welfare optimality of the equilibrium point. Furthermore, the system is shown to be input-to-state (ISS) stable when there are additive disturbances on the power measurements and the price, and the discrete-time implementation of the power management system is given. Simulation results demonstrate the balance between supply and demand and the stability of the system with and without disturbances.

1. Introduction

Smart grid is an intelligent power system that integrates advanced control, communications, and sensing technologies into the power grid [1]. In smart grid, demand response can motivate customers to shift their loads from on-peak to off-peak periods [2]. It is widely accepted that demand response is a more cost-effective way than providing enough generation capabilities to meet the peak load [3–7]. In general, there are two categories of demand response programs: incentive-based programs and price-based programs. The incentive-based programs include the direct load control program, the emergency demand response program, and the ancillary services market. For the price-based programs, the utilities can change the power consumption of customers by pricing, such as time of use (TOU), critical peak pricing (CPP), extreme day CPP (ED-CPP), extreme day pricing (EDP), and real-time pricing (RTP) [8]. Smart grid increases the opportunities for demand response by providing real-time data to providers and customers. In smart grid, the price can be provided to the customers in real time. For example, the electricity provider announces electricity prices on a rolling basis in the RTP program, and the price for a given time period (e.g., an hour) is determined and published before the start of the period (e.g., 15 min beforehand).

There exist a number of literature on the price-based demand response programs. Different demand response programs were developed based on game theory [9–11], stochastic optimization [12,13], intelligent optimization [14], and dual decomposition method [15,16]. The social welfare maximization was achieved by optimizing the individual utilities of the customers in the demand response program based on dual decomposition. Then, a distributed power control algorithm was proposed for demand response with communication loss [17]. The works mentioned above assumed that the price is adjusted according to a pricing algorithm instead of an explicit pricing function. Recently, a linear pricing function was developed to achieve the balance between supply and demand for smart grid [18,19], and a nonlinear pricing function was used to design a distributed demand response algorithm [20]. Nevertheless, few works are devoted to the social optimality of the distributed power control under nonlinear pricing function and the influence of the disturbances on the power control algorithm.

In this study, we use a quadratic pricing function and establish the conditions on the social optimality of the distributed power control algorithm. Due to the unavoidable disturbances on power systems, we further consider the distributed power control with additive disturbances on the power measurements and the price. The differences between our work and the other smart grid algorithms are shown in Table 1. To the best of our knowledge,

* Corresponding author. Tel.: +86 03357939689.
E-mail addresses: jyang.tju@gmail.com (J. Yang), Zhanggs@tju.edu.cn (G. Zhang), kma@ysu.edu.cn (K. Ma).

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Table 1
Comparisons with other smart grid algorithms.

	Pricing function	Disturbances	Social optimality
[11,18,19]	Linear	×	×
[9,20]	Nonlinear	×	×
[15,16]	×	×	√
[17]	×	Communication loss	√
Our work	Nonlinear	Additive errors	√

the social optimality of the distributed power control under the nonlinear pricing function and the influence of the disturbances on the power control algorithm have not been studied. The main contributions are as follows.

- The price-based demand response program is formulated as a nonlinear power management system.
- The condition is established for the equivalence of the equilibrium point of the system and the optimal solution of a social welfare maximization problem.
- The proof of the stability is given for the power management system with and without disturbances on the power measurements and the price.

The rest of the paper is organized as follows. In Section 2, the demand response program is formulated as a nonlinear power management system. In Section 3, the conditions of the price parameters are established for both the global asymptotic stability of the system and the social welfare optimality of the equilibrium point. In Section 4, the input-to-state (ISS) stability is shown for the system with disturbances on the power measurements and the price. The discrete-time implementation of the power management system is proposed in Section 5, and the simulation results are given in Section 6. Finally, conclusions are summarized in Section 7.

2. System model

As shown in Fig. 1, we consider a smart power system consisting of one electricity provider and N customers. The operation cycle of the power system is divided into several time slots. In each time slot, the electricity provider decides the electricity price and announces it to the customers. Then, the customers manage their power consumption according to the announced price.[1] We employ the utility functions to characterize the profits of the customers [21]. A quadratic utility function with linear decreasing marginal benefit is defined as

$$U_i(x_i) = \begin{cases} \omega_i x_i - \frac{a}{2}x_i^2, & \text{if } 0 \leqslant x_i \leqslant \frac{\omega_i}{a}, \\ \frac{\omega_i^2}{2a}, & \text{if } x_i > \frac{\omega_i}{a}, \end{cases} \quad (1)$$

where x_i is the power consumption of customer i ($i \in \{1, 2, \ldots, N\}$), ω_i ($\omega_i > 0$) denotes the willingness to increase the power consumption, and ω_i/a denotes the maximum demand of customer i. For instance, the utility functions with different willingness parameters are shown in Fig. 2. The quadratic utility function indicates that a customer is willing to choose larger power consumption with ω_i/a as the saturation value.

In general, the objective of demand response is to maximize the social welfare [22], which can be formulated as the following optimization problem:

[1] This assumption is for the economical theoretical behavior of the customers and is commonly used in other papers that studies price-based demand response, such as [9–11,15–20].

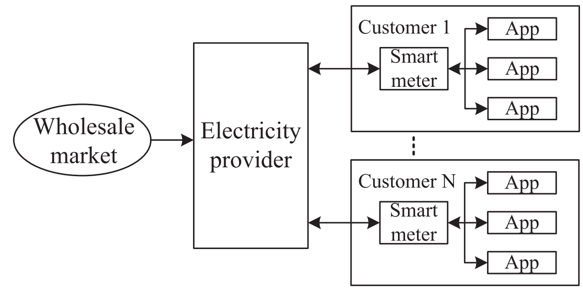

Fig. 1. Smart power system.

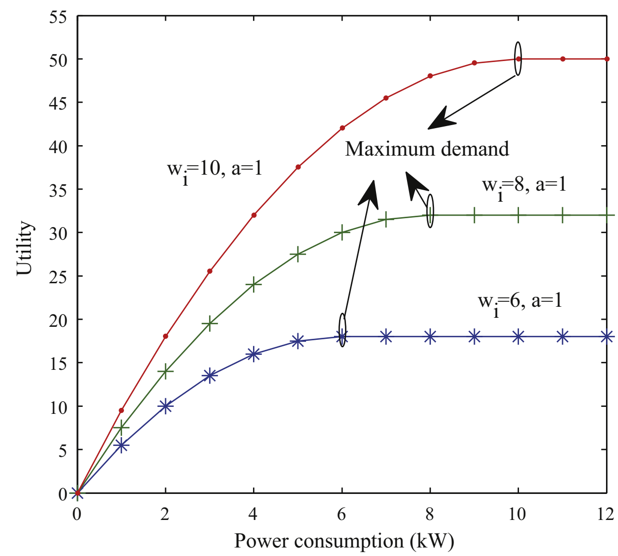

Fig. 2. Utility functions with different willingness parameters.

$$(\text{P1}): \quad \max \sum_{i \in \mathcal{N}} U_i(x_i)$$
$$\text{s.t.} \sum_{i \in \mathcal{N}} x_i = Q,$$

where Q denotes the power supply. The constraint in (P1) indicates that the total power consumption should match with the power supply. The optimization problem (P1) is a convex optimization problem and can be solved by the following primal algorithm [23]:

$$\dot{x}_i = k_i(\omega_i - a x_i - p(x)), \quad i \in \mathcal{N}, \quad (2)$$

where k_i is the control gain, $p(x)$ is the pricing function of the electricity provider, and $x = (x_1, \ldots, x_N)^T$ denotes the set of power consumption of all the customers. In this study, we select the quadratic pricing function:

$$p(x) = b\left(\sum_{i \in \mathcal{N}} x_i\right)^2 + c\sum_{i \in \mathcal{N}} x_i, \quad (3)$$

where b and c are positive price parameters. Eqs. (2) and (3) can be integrated in a nonlinear power management system, as shown in Fig. 3.

3. Stability and optimality

In this section, we will study the stability of the power management system (2) and (3). Before the proof, the definition of global asymptotic stability is given.