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Practical closed-loop dynamic pricing in smart grid for supply and demand balancing[☆]

Jianping He [a,b], Chengcheng Zhao [c], Lin Cai [d,*], Peng Cheng [c], Ling Shi [e]

[a] The Department of Automation, Shanghai Jiao Tong University, China
[b] The Key Laboratory of System Control and Information Processing, Ministry of Education of China, Shanghai, China
[c] The State Key Lab. of Industrial Control Technology, Zhejiang University, Hangzhou, China
[d] The Department of Electrical & Computer Engineering at the University of Victoria, BC, Canada
[e] The Department of Electric and Computer Engineering, Hong Kong University of Science and Technology, Hong Kong

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ABSTRACT

Pricing strategy for power systems is an important and challenging problem, due to the difficulties in predicting the demand and the reactions of customers to the price accurately. Any prediction errors may result in higher costs to the supplier. To address this issue, in this paper, we propose a novel, practical closed-loop pricing algorithm (PCPA). Using the closed-loop control to well coordinate the customers and the supplier, the power system can run more efficiently, resulting in both cost saving for customers and higher profit for the supplier. We prove the convergence of PCPA, i.e., a stable price can be achieved. We provide sufficient conditions to guarantee the win-win solution for both the customers and the supplier, and an upper bound of the gain. We also provide a necessary and sufficient condition of that the highest win for both the customers and the supplier can be achieved. Extensive simulations have shown that PCPA can outperform the existing prediction-based pricing algorithms. It shows that the profit gain of the proposed algorithm can up to 100% when the total demand can be fixed to the optimal demand.

1. Introduction

Enabled by new technologies, such as the intelligent and autonomous control, two-way communications between the power supplier and customers, and the advanced software-based data management, traditional power grids can be upgraded to smart grids that can intelligently incorporate distributed energy sources and deliver the power to customers efficiently (Fang, Misra, Xue, & Yang, 2012). Different from the traditional power grid, in smart grids, the supply and demand sides interact with each other by exchanging the price and demand information, aiming to minimize over-provisioning at the supply side (Yu & Hong, 2016). To improve efficiency, reduce peak load and balance the demand and supply, dynamic pricing has been advocated and become a promising technology (Borenstein, Jaske, & Rosenfeld, 2002; Chen, Wei, & Hu, 2013; Liang, Li, Lu, Lin, & Shen, 2013; Liu, Liu, Low, & Wierman, 2014; Samadi, Mohsenian-Rad, Schober, Wong, & Jatskevich, 2010; Sen, Joe-Wong, Ha, & Chiang, 2013; Tarasak, 2011). Based on dynamic pricing, considerable benefits will be gained by encouraging the customers to consume energy in a more efficient way (Deng, Yang, Hou, Chow, & Chen, 2015; Kim, Zhang, Schaar, & Lee, 2014; Wen et al., 2013; Zhang & Papachristodoulou, 2015). A proper dynamic pricing strategy cannot only smooth load demand curves to enhance the robustness and lower the generation cost of the power grid, but also reduce the electricity expenditures of the customers by reasonably scheduling their flexible electricity usage. However, how to design a proper dynamic pricing strategy is still a challenging problem given the difficulty in estimating the load accurately. The estimation errors are unavoidable due to the random demand, and the lack of knowledge in customers' preference and their reactions to price change (Joe-Wong, Sen, Ha, & Chiang, 2012; Qian, Zhang, Huang, & Wu, 2013; Wu et al., 2015). We refer the readers to the survey papers (Annaswamy, Hussainy, Chakrabortty, & Cvetkovic, 2016; Khan, Mahmood, Safdar, Khan, & Khan, 2016) for more details about dynamic pricing, price-based control and the corresponding open issues in smart grids.

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* Corresponding author.
E-mail addresses: jphe@sjtu.edu.cn (J. He), chengchengz@zju.edu.cn (C. Zhao), cai@ece.uvic.ca (L. Cai), pcheng@iipc.zju.edu.cn (P. Cheng), eesling@ust.hk (L. Shi).

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In the past few years, dynamic pricing in smart grids has attracted extensive attention, and many pricing schemes were developed in the literature, including real time pricing (Joe-Wong et al., 2012; Mohsenian-Rad & Leon-Garcia, 2010; Mohsenian-Rad, Wong, Jatskevich, Schober, & Leon-Garcia, 2010; Qian et al., 2013), time of use (Braithwait, Hansen, & Sheasy, 2007), and critical peak pricing (Kii, Sakamoto, Hangai, & Doi, 2014), and many more as discussed in Khan et al. (2016). The existing pricing schemes can be divided into two categories. The first one aims to maximize the profits of customers, and deals with how the customers schedule their flexible electricity usage to achieve their desired level of comfort with a lower electricity bill payment based on the prediction of future price (Mohsenian-Rad & Leon-Garcia, 2010; Mohsenian-Rad et al., 2010). The second takes both the customers' cost and the supplier's profits into consideration, and deals with how to determine the appropriate prices according to the prediction of the customer's energy consumption and their reaction to a given price (Braithwait et al., 2007; Chen, Li, Low, & Wang, 2010; Joe-Wong et al., 2012; Kii et al., 2014; Kim et al., 2014; Li, Chen, & Low, 2011; Paschalidis, Li, & Caramanis, 2012; Qian et al., 2013; Roozbehani, Dahleh, & Mitter, 2010a; Samadi et al., 2010; Tarasak, 2011). There is a common feature for these existing schemes, i.e., the decision was based on the prediction of the future price or the customers' reaction on a given price. In other word, the scheduling at the customer side is based on future price prediction, and the pricing determined by the supplier is based on the demand prediction. Hence, they study an open-loop decision problem from the perspective of control theory given the prediction-based decision, and thus these existing scheduling and pricing strategies are named as open-loop scheduling and pricing in this paper. Since the scheduling at the demand side and the pricing at the supply side are separated, it will cause high cost for both the customers and the supplier when the prediction is not accurate. For instance, a very high cost will be caused to the supplier when the customers' demand determined by their scheduling strategy is greatly deviated from the total amount of the electricity provided by the supplier. In contrast, if the loads are delayed to a high cost time interval, the customers will have much higher utility bills. In order to make wise pricing decisions, the price and demand information should be exchanged between the supply and demand sides, and then we can optimize the strategies for both.

Therefore, Roozbehani et al. (2010a) and Roozbehani, Dahleh, and Mitter (2010b) proposed closed-loop dynamic pricing algorithms to achieve a stable price by constructing a feedback loop between the customers and the supplier. The proposed algorithms can achieve a very good performance when the supplier follows demand precisely. Inspired by these works, in this paper, we further investigate the closed-loop pricing in a more realistic scenario, and the assumption that supply follows demand precisely is removed, so the randomness at the demand side is taken into consideration. We first design a novel practical closed-loop pricing algorithm (PCPA) using a piecewise pricing approach. The proposed algorithm largely improves the system efficiency and results in both cost savings for customers and higher profits for the supplier, and thus achieves a win-win solution. In summary, compared with the existing open-loop pricing, PCPA can largely decrease the probability of high cost and thus potentially save the cost a lot. Compared with the existing closed-loop pricing algorithm, firstly, our algorithm relaxes the assumption. Then, a piecewise pricing approach is adopted in PCPA, where a much higher price is used for the penalty and a lower price is used as incentive to the customers, rather than the single pricing approach used in the most existing literatures. Lastly, PCPA achieves a win-win solution for both the customers and the supplier.

The details of the PCPA have been introduced in our conference paper (He, Zhao, Cai, Cheng, & Shi, 2015). In this paper, we have improved the PCPA, and added an optimal open loop pricing algorithm to obtain the initial price. We also have improved the theoretical results on the win-win solution and added the proof to make it rigorous. In addition, the optimality analysis for the proposed algorithm is provided. We obtain the upper bound of the profit gain (i.e., the win) and its necessary and sufficient condition. The condition to achieve the lowest price using the proposed pricing scheme is obtained. The main contributions of this work are summarized as follows.

- We develop a novel and practical closed-loop pricing framework for supply and demand balancing, where the randomness of the customers' demand and the cost caused by the deviation between the real demand and the desirable load for the supplier, have been modeled.
- We analyze the disadvantages of open-loop-based pricing algorithms, and reveal the potentially higher cost of the algorithms especially when the total demand is larger than the maximum supply. To solve this problem, we propose a novel practical closed-loop pricing algorithm (PCPA) using a piecewise pricing approach, where a much higher price is used for penalty and a lower price is used as incentive to the customers.
- We prove that the proposed algorithm can achieve a stable price and a win-win solution for both the customers and the supplier. Meanwhile, we provide the optimality analysis, where the upper bound of the profit gain and its necessary and sufficient condition are obtained.
- Extensive simulations are conducted to demonstrate the effectiveness of the proposed algorithm. It shows that PCPA can outperform the existing prediction-based pricing algorithm by a profit gain up to 100% (when total demand is fixed to the optimal point).

The remainder of the paper is organized as follows. In Section 2, the problem of the pricing problem is formulated. Section 3 analyzes the disadvantages of the open-loop pricing algorithm. The closed-loop algorithm is introduced in Section 4 and its performance analysis is given in Section 5. Simulation results are presented in Section 6 for performance evaluation. Finally, Section 7 concludes the paper.

2. Modeling and problem setup

2.1. System model

Consider a smart grid consisting of the electricity supplier (supply side), end-users or customers (demand side), and a control center, as shown in Fig. 1. On the supply side, the supplier generates the electricity and sells it to the end-users. On the demand side, each customer purchases the electricity from the supplier to satisfy its electricity demand. The control center is a not-for-profit organization responsible for determining a price in order to balance the supply and the demand. This role of the control center is the same as the Independent System Operator (ISO) proposed in Roozbehani et al. (2010b).

In the above system model, suppose that both the supplier and the customers can communicate with the control center to exchange the price and the demand information. The time of each day is divided into multiple time-slots. The slot duration of each time-slot is given and set by the control center, which is made by a tradeoff between the amount of flexible load (the longer the duration, the less flexible demand) and the system complexity (Tarasak, 2011). In order to determine an appropriate price of a unit electricity, the control center will simultaneously consider the cost and profit functions of both the customers and the supplier at the beginning of each time slot. In this work, the time-correlation