Applied Energy 205 (2017) 236–243

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Dynamic pricing for responsive demand to increase distribution network efficiency

Chenghong Gu[a], Xiaohe Yan[a,*], Zhang Yan[b], Furong Li[a]

[a] Dept. of Electronic and Electrical Eng., University of Bath, Bath BA2 7AY, UK
[b] State Power Economic Research Institute, Beijing, China

HIGHLIGHTS

- Relates system operation to investment varying at different time granularity.
- Quantifies the cost according to customer contribution to network congestion.
- Introduces a dynamic pricing scheme to reflect demand response on the two costs.
- Translates customer impact on networks into effective economic signals.

ARTICLE INFO

Keywords:
Network congestion
Investment
Demand response
Tariff
Load curtailment
Generation curtailment

ABSTRACT

This paper designs a novel dynamic tariff scheme for demand response (DR) by considering networks costs through balancing the trade-off between network investment costs and congestion costs. The objective is to actively engage customers in network planning and operation for reducing network costs and finally their electricity bills. System congestion costs are quantified according to generation and load curtailment by assessing their contribution to network congestion. Plus, network investment cost is quantified through examining the needed investment for resolving system congestion. Customers located at various might face the same energy signals but they are differentiated by network cost signals. Once customers conduct DR during system congested periods, the smaller savings from investment and congestion cost are considered as the economic singles for rewarding the response. The innovation is that the method translates network congestion/investment costs into tariffs, where current research is mainly focused on linking customer response to energy prices. A typical UK distribution network is utilised to illustrate the new approach and results show that derived economic signals can effectively benefit end customers for reducing system congestion costs and deferring required network investment.

1. Introduction

In the new energy landscape with increasing renewable energy penetration, regulators require network operators to justify their investments in order to reduce the cost of decarbonisation. The aim is not only to maximize resources but also safeguard the interests of vulnerable end customers. For example, the new regulatory framework in the UK for distribution network operators-RIIO by the Office of Gas and Electricity Markets (Ofgem) has placed a strong emphasis on developing innovative and efficient network solutions, where demand response (DR) is a key player [1]. Thus, network investment might not be the most economic option for system operators to ensure sufficient network capacity. On the other hand, enabled by smart metering, customers can change their electricity usage in response to the conditions of networks and generation, which is defined as demand response. In the UK alone, 53million smart meters will roll out by 2020 to all homes and small businesses [2].

DR can be achieved through sending economic signals to customers, which comes in the form of pricing. By far, there is a large volume of research on dynamic pricing schemes, but most of them aim at energy costs that customer confront [3,4]. In [5], tariff design very much focuses on transforming flat rates into time-of-use tariffs so that tariffs vary over time to enable end customer response. Some efforts have been dedicated to designing dynamic pricing, which can reflect the energy cost variation at the wholesale market. Work in [6] falls into this category.

---

* Corresponding author.
E-mail address: xiaohe_yan@yahoo.com (X. Yan).

http://dx.doi.org/10.1016/j.apenergy.2017.07.102
Received 6 March 2017; Received in revised form 1 July 2017; Accepted 24 July 2017
0306-2619/

Stochastic quadratic programming techniques are used to set the price signals for pricing elasticities of demand in [7]. It considers the aspects such as economic efficiency promotion, revenue adequacy assurance and incentives provision to maximize total economic welfare. However, the economic signals cannot reflect the impact of network condition from customers. Paper [8] focuses on the balancing between demand side operation and investment activities to maximize the profits that cover both operation and investment based on Short-Run Marginal Cost (SRMC) pricing. Paper [9] proposes cost reflective pricing signals to Low Voltage (LV) grid users by quantifying their degree of cross-subsidies.

On the other hand, network costs account for a large proportion of end customer bills. In the UK, network costs, in terms of Use-of-System (UoS) charges take up around 25% of bills. This justifies that dynamic tariffs to customers should reflect not only energy costs but also network operation and investment costs. In this way, the economic signals can incentivise customers to avoid using electricity during network peak or congested periods so that required network investments can be delayed or avoided. Further, in order to manage network congestion, it is important that when large flexible loads are connected to networks, such as Electric Vehicles (EVs) and heat pumps. networks are notified, but currently, these loads are notified to DNOs (Distribution Network Operators) in an inconsistent or inaccurate manner. This creates great challenges to DNOs as the condition of their networks is partially invisible to them. Therefore, it is essential for DNOs to have some instruments to control/influence the invisible demand.

Dynamic pricing is one of the effective economic tools [10]. There are several papers focusing on dynamic pricing design combined with other methods, such as energy management, to generate economic signals to influence flexible loads and malicious users who cannot comply with pricing programs. Papers [11,12] consider dynamic pricing for demand management. The degree of usage flexibility is offered by focusing on dynamic tariffs derived based on the actual costs from power markets. Paper [13] uses dynamic pricing to address centralised DR, which also designs approaches to avoid DR centralising caused by the combination of DR to the same economic signals. Paper [14] uses reinforcement learning algorithms to analyse the dynamic pricing and energy consumption between customers and utility companies in a microgrid. A new dynamic pricing is designed for DR which can ensure cost savings for flexible load in [15]. Paper [16] uses a dynamic pricing algorithm for unstable energy use and malicious users in smart grids to flatten load profiles. The impact of dynamic pricing on peak demand, supplier profits, energy bills and congestion costs are analysed in paper [17].

To summarise, most previous work is focused on designing price signals based energy prices, i.e. the relation between suppliers/retailers and customers, but limited attention has been devoted to designing cost-reflective pricing schemes that reflect for network costs. Papers [18,19] quantify the impact of DR on network investment costs but do not design tariff schemes to reflect the costs in end customers' bills.

In order to fill the research gap, this paper designs dynamic tariffs considering network costs, which primarily are distribution network costs. Thus customers, who respond to networks conditions, can benefit from operation and investment cost reduction. This paper first fights the balance between network investment costs and congestion costs. System congestion costs are quantified according to generation and load curtailment by assessing the contribution to network congestion. Network investment cost is quantified by assessing the required investment for resolving system congestion. A power transfer distribution factor (PTDF) is utilised to assess nodal power impact on branch flows, which is then translated into the change of network reinforcement horizon. Once customers conduct DR during system peak periods, the smaller saving between network investment and congestion cost is considered as economic singles for rewarding the response. This approach determines not only the magnitude of operation and investment costs but also the occurrence times so that they can be easily translated into time-varying economic signals.

The main contributions of this paper are as follows: i) it relates system operation to investment approaches that vary at different time scale and studies the interaction of the two methods for addressing network congestion; ii) it introduces a dynamic pricing scheme to reflect customer response on system congestion cost and investment cost and designs a cost-reflective pricing scheme; iii) it translates customer impact on networks into economic tariffs so that they can be used to affect customer energy use for improving network efficiency.

The rest of the paper is organised as: the relationship of network congestion cost and investment cost are discussed in Section 2, which shows the approach for addressing network congestion. The methods for calculating these two costs are provided in Section 3. In Section 4, the method for translating the two costs into network tariffs for customers that conduct demand response under various conditions is introduced. The method is verified by a practical network in Sections 5 and 6 concludes the paper.

2. Network investment cost and congestion cost

Network investment and operation are two options for DNOs to manage their networks in order to accommodate generation and demand. Network congestion is caused by limited network capacity to transfer electricity. Generally, the two costs are:

- Congestion cost: Distribution generators or demand needs to be curtailed to alleviate network congestion and save network investment, and thus the congestion cost is quantified as the cost to curtail generation or demand.
- Investment cost: On the other hand, network investment can be conducted to remove congestions, and the investment cost is the total asset cost plus labor cost and installation costs. Investment cost is normally annuitized over the lifetime of an asset so that it can be recovered on a yearly basis.

From an economic aspect, there should be an equilibrium between network investment cost and congestion cost. If total annual congestion cost is larger than annual investment cost, it is more economical to reinforce the networks, otherwise to conduct network operation (see Fig. 1).

Under this new environment, the relationship between customers and networks becomes more flexible. During peak demand periods, demand shifting/reduction bring benefits of investment deferral and it can also reduce network congestion costs if it can remove network consumption away from system congested periods. The challenge in finding the balance between the two costs is that congestion cost is short-term normally within hours, but investment cost is long-term and varies at year scale.

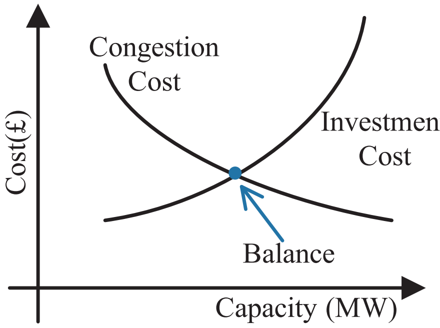

Fig. 1. Trade-off between investment and congestion costs.