ECONOMIC AND OPERATIONAL IMPLICATIONS OF DEMAND CHARGE FOR DISTRIBUTION SYSTEMS WITH RENEWABLE ENERGY

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ABSTRACT

Demand charge is a tariff option widely used in commercial and industrial sectors. As the demand charge bills on the peak load within a specified period, it is considered a useful pricing tool when the net electricity usage is declining due to distributed renewable integration. We study the retail tariff design problem with demand charge to maximize the social welfare while maintains the utility's break-even constraint. A Stackelberg game model is adopted to describe the interactions between the retailer and consumers. The tariff design problem is then formulated as a bi-level programming model and transformed into a mathematical program with equilibrium constraints (MPEC). Real-world demand and tariff data are used to show the economic and operational benefits of three different tariff designs.

INTRODUCTION

The increased penetration of distributed renewable energy (DRE) has caused problems such as declining kWh sales and rising peak-valley difference. These issues would risk the financial viability of utilities and bring challenges for the operation of distribution systems. The demand charge is what industrial and commercial customers pay for their peak demand within a certain billing period. And in some regions, the demand charge has been adopted as an optional structure for residential consumers with distributed solar PV[1]. As a kind of stand-by costs, the demand charge has been widely adopted for fixed investment cost recovery and lowering the peak-valley load difference in the system. In this paper, we are interested in the design of retail tariffs with the demand charge to improve the overall social welfare and load ratio under DRE penetration.

Researchers interested in the demand charge have been working on various strategies for reducing the consumers' electricity payment facing it. In [2], an expectation-oriented demand contracting model is proposed under uncertainty. [3] studies on how storage can be used for demand charge reduction. Concerning retail tariffs, numerous works have been in place on the users' demand response facing different retail energy prices[4-6]. Other research focuses on designing economically efficient tariff to achieve different objective[7, 8]. The most

relevant papers to our work are [9, 10], where the economic efficiency of two-part tariffs with connection charges is studied considering DRE adoption.

The main contribution of this paper is the formulation of the pricing model for the demand charge considering demand response, which is formulated as a bi-level optimization model. We provide an interesting perspective that customers can also optimize their usage pattern in response to the setting of demand charges. Given the pricing model, we further investigate how the adoption of demand charge could help improve the retail market efficiency and reduce the peak-valley demand gap in the presence of DRE.

MODELS

We study how a regulated utility can use the kind of retail pricing policy, so-called demand charge, to acquire economic and operational benefits in distribution systems. The retail tariff design of a monopolistic electric utility is established as a Stackelberg game model, where the utility and customers take the roles of leaders and followers respectively. Explicitly, the utility considers rational customers' response in their demand profiles while designing retail tariffs. We cast more light on the design of demand charges which, due to the billing cycle, seldom appear when it comes to demand response areas. That said, with the increasing deployment of smart metering devices, such design can become more practical. The customers' utility is assumed to be a function of their load profiles. In this work, we simplify the loads to be purely thermostatically controlled loads (TCLs), for example, air conditioners. The model of TCLs has been studied extensively, thus in this part, we adopt similar representations as in [11], where the utility is captured by a quadratic function. The customers' monetary utility of consuming energy q is given by

$$S(q) = \delta - \frac{1}{2}(\omega - q)^{\top} G^{-1}(\omega - q) \qquad (1)$$

where δ is a constant of the customers' surplus, G deterministic and positive (representing customers' elasticity in demand), $\omega \in R^{N}$ the original states of customers, N the number of periods in a billing cycle, and $q \in R^{N}$ the aggregated load profile of consumers.

Consumers' electricity payment to the utility consists of two parts. One is the volumetric price for per unit electric

energy they consume, and the other is dependent on the maximal demand in each billing cycle, which is assumed to be one day in this paper (notice that the typical billing cycle for demand charge is one month). One reason for adopting such a tariff structure is that the utility is experiencing difficulties recovering its fixed operating cost merely from the volumetric price due to the decreasing net demand caused by DRE integration. It turns out that the demand charge is well suited for this problem. Hence, consumers' electricity payment can be represented by

$$B = \pi^\top (q - r) + \eta p \tag{2}$$

where $p \in R$ is the peak demand throughout the billing cycle, r the renewable generation profile, $\pi \in R^N$ the volumetric price vector, and $\eta \in R$ the demand charge.

The consumers' surplus is equivalent to the monetary utility subtracted by the payment of electricity. Thus, the lower level of our problem, which features the behaviors of consumers, is given by:

$$\max_{q,p} \quad S(q) - \pi^\top (q - r) - \eta p$$
$$\text{s.t.} \quad q_i - r_i \le p, \text{ for } i = 1, ..., N \tag{3}$$

Since $p = \max\{q_i - r_i\}$ involves complicated judgment in modeling, we use the constraint $q_i - r_i \le p$ to limit the value of p. It is clear that the solution is located where the minimum number (yet is greater than 0) of equalities of these constraints is available.

The electric utility in this paper is assumed to be a Ramsey planner who would maximize the social welfare while maintains the financial viability of the utility itself (by satisfying its revenue adequacy). Therefore, the upper-level problem can be specified

$$\max_{\pi, \eta} \quad S(q(\pi, \eta)) - \pi^\top (q(\pi, \eta) - r) - \eta p(\pi, \eta)$$
$$\text{s.t.} \quad (\pi - \lambda)^\top (q(\pi, \eta) - r) + \eta p(\pi, \eta) = C \tag{4}$$

where $q(\pi, \eta)$ and $p(\pi, \eta)$ are the solutions of the lower-level problem, C the fixed operating cost of the utility.

The consumers' (followers') problem can be reformulated as

$$\Phi(q, p) =$$
$$\arg\max_{q,p} \left\{ \begin{array}{l} \delta - \dfrac{1}{2}(\omega - q)^\top G^{-1} (\omega - q) - \pi^\top (q - r) \\ -\eta p : q_i - r_i \le p \end{array} \right\} \tag{5}$$

The bi-level problem can then be written as

$$\max_{\pi, \eta} \quad \delta - \dfrac{1}{2}(\omega - q)^\top G^{-1} (\omega - q) - \pi^\top (q - r) - \eta p$$
$$\text{s.t.} \quad (\pi - \lambda)^\top (q - r) + \eta p = C \tag{6}$$
$$q, p \in \Phi(q, p)$$

As the lower-level program has concave objection function and linear constraints, the solutions of the lower level problem can be characterized by its Karush–Kuhn–Tucker (KKT) conditions. Therefore, the bi-level problem can be transformed into a mathematical program with equilibrium constraints (MPEC), given by

$$\max_{\pi, \eta, q, p, \mu} \quad \delta - \dfrac{1}{2}(\omega - q)^\top G^{-1} (\omega - q) - \pi^\top (q - r) - \eta p$$
$$\text{s.t.} \quad (\pi - \lambda)^\top (q - r) + \eta p = C$$
$$G^{-1}(\omega - q) - \pi - \mu = 0 \tag{7}$$
$$\sum_1^N \mu_i - \eta = 0$$
$$0 \le \mu_i \perp p - q_i + r_i \ge 0$$

where $\mu \in R^N$ is the Lagrange multiplier.

The reformulated problem has nonlinear and complementary constraints which make it hard to get the global optimum. However, over the years, the solutions of MPEC problems have been studied extensively. A typical solution method is to linearize some of the constraints and transform the problem into a mixed integer linear program and then put it on commercial solvers. The detailed solution process yet is not the focus of our paper, and readers interested in how to solve MPEC problems are referenced to [12].

NUMERICAL CASES

In this section, numerical cases are provided to demonstrate the economic and operational benefits of the demand charge using the proposed model.

We use publicly available real-world demand and tariff data in this section. And although these data come from residential users, similar conclusions can be drawn for commercial and industrial customers as well.
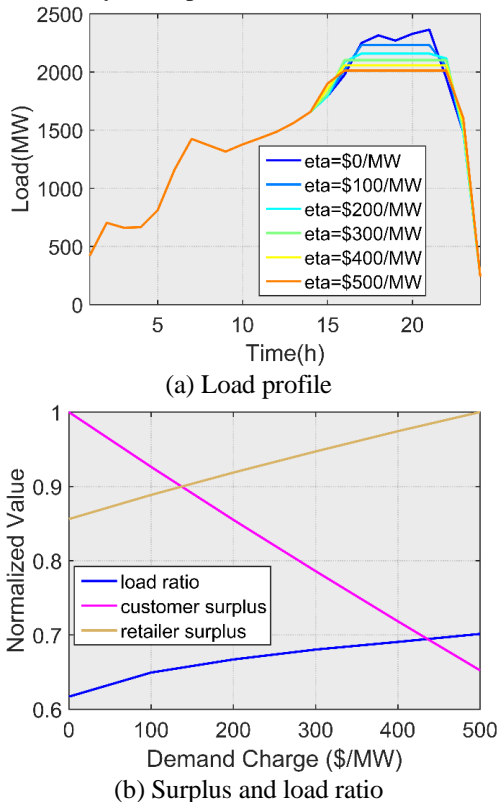
Customers' response

This basic example is used to show how customers will change their load profiles in response to increasing demand charges. The volumetric price is fixed in this case. We illustrate in Fig.1(a) the customers' load profiles under different demand charges. The demand charge η (or eta in the figure) ranges from \$0/MW to \$500/MW with the interval set to be \$100/MW. This figure reveals that with rising demand charges, customers reduce their peak load while shift part of it to the off-peak periods. A nearly 15% reduction occurs in the peak load under η =\$500/MW compared to that under η =\$0/MW. On the other hand, the total energy usage throughout the day also drops by around 220MW.

In Fig.1(b), we show how the load ratio, consumer surplus, and the retailer surplus would change in accordance with increasing demand charges. Fig.1(b) shows that the system load ratio and the retailer surplus increase with demand charge increments, yet the consumer surplus becomes lower. This implicitly shows that raising demand charges is a possible way to recover increasing fixed operating costs, and we compare its performance with raising the volumetric price in the next two subsections.

Furthermore, the increasing retailer surplus also shows that even if the volumetric price is somewhat reduced, the revenue of the retailer can still be maintained through demand charges. Another benefit clear from the figure is

that the peak-valley difference is reduced, which relieves the burden of system operation.

(a) Load profile

(b) Surplus and load ratio

Fig. 1 Consumers' response to demand charges.
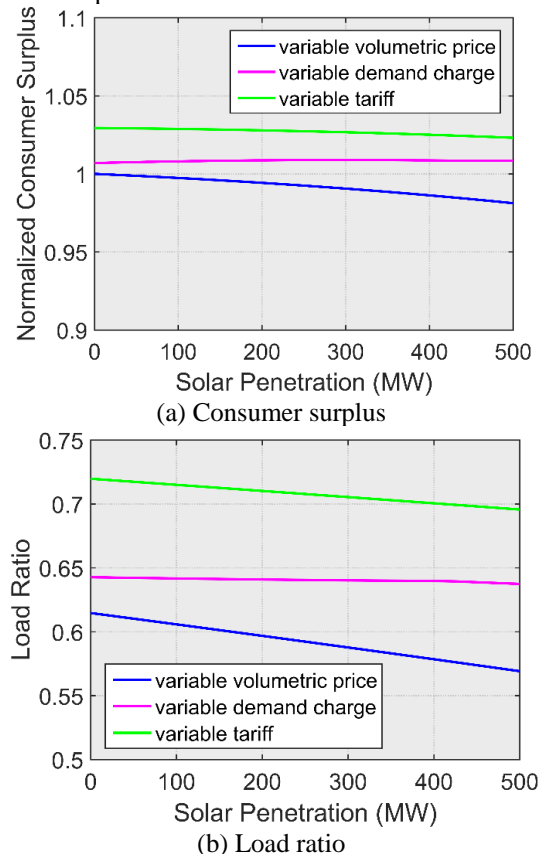
Increasing solar penetration

In this subsection, we look at the performance of different pricing schemes under increased solar penetration. Three possible tariff designs are studied here: fixed demand charge with variable volumetric price, fixed volumetric price with variable demand charge, both parts of the tariff variable.

In Fig.2, we set the solar integration to 200MW, and the utility adopts the three tariff designs to plan its tariff as specified in (4). We plot how rational customers adjust their demand profiles in response to the tariffs as modeled in (3). The results show that while pure variable demand charge can reduce the peak-valley difference (increase the load ratio), this effect becomes even more significant when both parts of the tariff are modifiable.
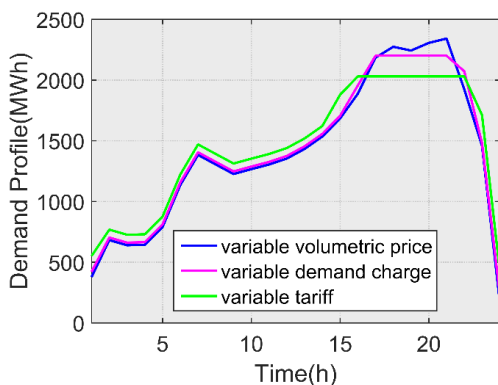
Fig. 2 Demand profile with solar penetration 200MW.

In Fig 3, we show how normalized consumer surplus and load ratio evolve under different tariff designs when the solar integration increases. Note that for a Ramsey planner, the retailer surplus is constrained to be a constant, which equals the fixed operating cost. It is thus reasonable to use the term consumer surplus instead of social welfare, which is the sum of the consumer and retailer surpluses. The figure shows that when the volumetric price is variable, the consumer surplus and load ratio have a clear declining trend with solar integration. While under variable demand charge, this trend is not obvious, and Fig.3(a) even demonstrates a slightly increasing trend. The overall performance of the three designs is direct, under all solar integration as studied in this work, the variable two-part tariffs result in more favorable consumer surplus and load ratio than the other two. And the variable demand charge design outperforms the variable volumetric price one. The figure also shows that the demand charge can keep the consumer surplus and load ratio from dropping too much while satisfying the retailer's break-even requirements under solar penetration.


(a) Consumer surplus

(b) Load ratio

Fig. 3 Different tariff designs with solar penetration.

Increasing fixed operating cost

We check another series of cases where the retailer's fixed operating cost is increasing, say in our case, by 2% every year.

In Fig. 4(a), we plot the normalized customer surplus under the three tariff designs with rising fixed operating cost. The figure shows that the consumer surplus in all tariff designs decreases, and the demand charge still

shows its advantage in lowering the decreasing speed. The figure also shows that changing both parts of the tariff still outperform the other two, yet its gap with adjustable demand charge is getting smaller with more solar integration.

In Fig 4(b), the performance of the three tariff designs is in the same order as in Fig. 4(a). We can also notice that the demand charge can even boost the load ratio facing increased retailer costs.

(a) Consumer surplus

(b) Load ratio
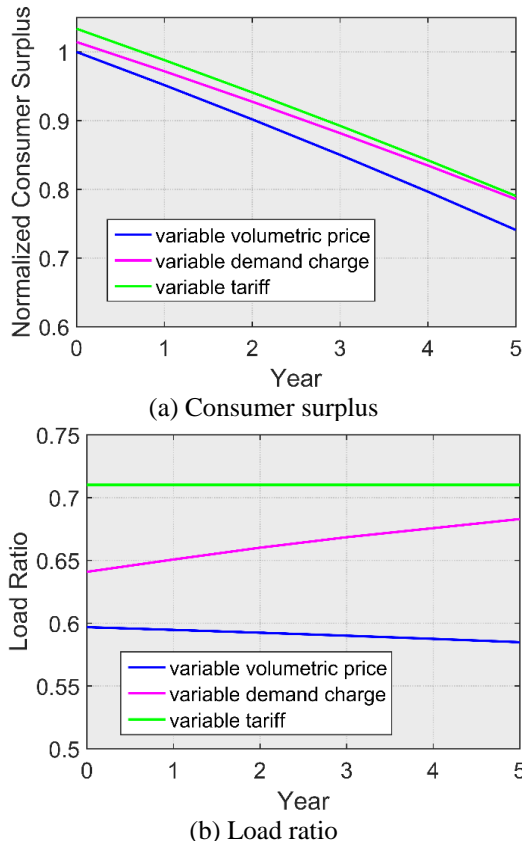
Fig. 4 Different tariff designs with increasing cost each year.

CONCLUSIONS

In this paper, the retail tariff design is studied especially with the existence of demand charges. The Ramey pricing is adopted as the basic pricing rule.

Specifically, we look at three tariff designs adjusting each part of the tariff facing exogenous inputs such as distributed solar integration and increase of the fixed operating cost. We show that purely changing the volumetric price is undesirable in terms of both social welfare and load ratio. The role of demand charge is important in maintaining the performance (smooth or even stop the decrease of social welfare and load ratio) facing these exogenous inputs. We suggest designing the volumetric price and demand charge jointly, so as to gain most in economic and operational benefits.

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