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A Value-based Real Time Pricing Under Imperfect Information on Consumer Behavior

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Abstract — One of the major challenges confronting a multiservice electric utility is the establishment of the right prices for its services. The key objectives of particular pricing schemes are reasonableness of company earnings, economic efficiency, the responsiveness of supply and of the allocation of sources to the desires of consumers, and maintenance of some degree of competition. This paper proposes a value-based pricing mechanism amenable to the current deregulation situation in electricity market allowing service differentiation. The proposed pricing mechanism can be implemented in a nodal auction model, and can also be applied to direct load control.

1. Introduction

Throughout the past decades, the electric utility industry has confronted major changes in its operating environment. Many of these changes were of an economic nature, such as rapid rise in financial costs and fuel prices. At the same time, rising utility rates have provoked consumers' ire and calls for greater consumer input into utility regulation. Moreover, the prospect of increased competition from decentralized generating sources has spawned support for deregulation of electric generation and prompted some utilities to explore diversification outside of the regulated utility business.

Concerns such as these have radically altered the concept of utility planning by infusing discussion of technical and economic issues with questions of political viability and corporate social responsibility. Competition is now forcing the utilities to operate more efficiently, plan their investment in a more prudent manner and devise their pricing policies more efficiently.

Properly designed service options have the potential for enhancing the economic efficiency of the entire system, producing benefits for both the utility and its customers. With unbundled service, reliability options and investments will be targeted and charged to those customers willingness- to-pay (WTP) for a premium service. As a result, subsidies between customers will be reduced and rates will better match the service received (producing a Pareto Optimal where the service provided better matches individual customer needs). In other words, systemwide application of value-based rate designs can provide more consistent and efficient resource allocation decisions within and across each system function.

Although the number of innovative pricing schemes has increased for the past few years, most customers are still provided with uniform service of the same high reliability and quality. A single service standard which ignores the considerable distribution of customer needs for quality, reliability, and willingness-to-pay results in an inefficient allocation of investment within the system and the uneconomic distribution of energy among customers.

This same situation also applies for the reverse situation, where the utility pays qualified producers a single price that does not differentiate between the quality and reliability or recognize the distribution of customer valuations, at different times and locations, for the power provided. For example, highly reliable alternative generation that is located within easy access of customers with a need for a more reliable source of power will have much greater value than an equivalent resource where access is infeasible or achievable only at additional cost.

Under a single service standard, all customers pay for the current level of reliability and quality whether they need or not. Those requiring less than the system standard will pay more for their service than necessary subsidizing those who require the higher service levels. Those requiring more than the system standard will pay less and receive less than their applications of electricity might otherwise justify. Furthermore, in a competitive electricity market where all the network facilities and equipments are increasingly required to be operated at their ultimating ratings, an efficient rate design for the corresponding service is of great importance.

This paper proposes a value-based pricing mechanism under the current deregulation situation in electricity market allowing service differentiation, especially in transmission service.

In this paper, we first give a brief summary on the value-based rate design and real-time pricing in the next section. Then ,in Section 3. the key features of the proposed pricing scheme with revenue reconciliation are provided, followed by the concluding remarks.

2. Value-based Rate Design

Applications employing a value-based pricing scheme and planning techniques were first introduced by several European power systems during the 1950's. The principal application was the use of outage costs to establish an efficient pricing scheme as well as the optimal level of system reliability. Outage costs have been used as a basis for balancing expected customer costs incurred from a loss of service against expected system costs to provide service.

Sweden, Norway, and France have pioneered the use of outage costs in optimizing system reliability. In early 1980s, Ontario Hydro and Sackatchewan Power Corp. in Canada. and Electrobras in Brazil had switched to economic reliability standard as well[2]. Some Asian countries, including Japan and Korea, also have started studying the evaluation and use of outage cost in the late 1980s[3].

There have been a number of studies on outage cost and its application in the US during the past fifteen years. Most of these studies have been limited in scope and conceptual detail, however. Related research projects funded by EPRI and DOE have, because of scope limitations, focused primarily on theoretical aspects or limited applications of outage costs. Although it is clear that the application of the concept of value-based service has long been studied in many countries, only few theoretical and empirical efforts have been exercised in developing the value-based pricing schemes

The earliest studies of the value-based pricing, mostly in the form of priority pricing scheme, stem from the work of Oren, Smith, and Wilson[4]-[6], and later the theoretical foundation of priority pricing, its efficiency properties and the relations between priority pricing and real-time pricing have been investigated by Chao and Wilson[7]-[9]. Further studies of the pricing of capacity and usage, and of priority service have been reported in Chao, Oren, Woo, and Wilson[10]-[13].

Siddiqi and Baughman present a comprehensive theory of reliability differentiated pricing (RDP) that combines elements of both real-time pricing and priority pricing[14]. The novelty of this pricing scheme lies in a fact that customer outage cost is adopted as a component of spot prices. At the same time, their theory is predicated on a number of assumptions that seem vulnerable to attack, particularly assumptions on outage cost and consumer behavior.

The key element of RDP is the use of customer outage costs as a component of real time prices. It is assumed, in the case of a shortage of supply, that customers behave along the 'very short run' demand curve in order to minimize losses due to outage. That is customers pay extremely high premium charge for continued service.

Real-time Pricing(RTP) is based upon the economist's view of marginal costs. The real-time prices for buying and selling electricity are determined by the supply and demand conditions at that moment[15]. They reflect the marginal operating costs of producing electricity on a real time basis.

The first among the practical issues that confronts RTP implementation is the problem of the duration over which a given price quote will hold. In theory, the spot prices will change continuously and instantaneously. Unless a major disruption occurs, one would not expect that changes in the spot price to be large in short intervals of time. However, over the hours of the day, there are large swings in the load that needs to be served. Thus, different prices over the hours of the day will be necessary to reflect the cost changes. The longer the update interval on the prices, the larger will be the price changes from one interval to the next. At the same time, the longer the update interval the longer will be the time that the precise price quoted will not be an accurate reflection of the costs of supply in that interval. The RTP experiments that are currently underway typically use a one hour update interval as a compromise.

A second consideration that affects the spot market pricing lies in being able to determine the price responsiveness of various customers and customer classes. The amount of the curtailment premium that needs to be included in the real-time prices at times when there is a lack of sufficient generating capacity is dependent upon the price responsiveness of the customers, individually and collectively, who will pay the curtailment and congestion charges. The amount of the congestion charge that needs to be included in the real-time prices at a specific location to limit the transmission flow to the available capacity of the line serving the area when it otherwise would be overloaded is also dependent on the price responsiveness of the customers served in that location by that line. Thus, implementation of RTP requires more detailed and accurate information about consumer electricity and consumption preferences than is currently available.

In our study, however, the consumer' behaviour to the diversified service quality is assumed to be revealed as the real-time response to the corresponding price signal

3. Key Features of the Proposed Pricing Scheme

The central idea of the pricing scheme proposed here is to diversify the service quality, for instance, system reliability, based on individual customer' (or, group') utility function to induce the maximum social welfare. It exploits the existing idea of 'Products-Differentiation'. It is, however, completely different from previous ones which are concerned with only price and quality choices. In this pricing scheme, multi-choice of service quality is possible, so a consumer selects his optimal set of price, quality as well as quantity.

It will also exploit the concept of self-selecting tariffs. Self-selecting tariffs have recently become popular for a variety of reasons. Under traditional assumptions about customer behavior, self-selecting tariffs provide utilities and their regulators with a mechanism for increasing surplus. Not all self-selecting tariffs, however, allow for Pareto dominance or even increase surplus. When not appropriately designed, the introduction of this can decrease surplus.

As mentioned, the appropriate design of tariffs requires information on the demand of customers, which the rate maker generally does not possess. Our pricing scheme will be designed to increase surplus, and, in equilibrium, to reach first-best optimality, without the regulator or rate maker knowing perfect information on consumers' purchasing behavior[16]. It is noted, however, that when applied to the regulated transmission system, it yields the so-called second best pricing accompanied by some type of revenue reconciliation.

3-1. Utility Function and Pricing

In general, the perceived value or satisfaction that a customer receives from their electric service can be viewed as equivalent to a measure of economic utility. The concept of economic utility assumes that each individual customer will allocate available income among various goods and services in such a way as to maximize their level of satisfaction. It is not possible to objectively quantify the absolute amount of *satisfaction* derived by a household corresponding to any given consumption pattern. However, the perceived value of any item in the consumption basket can be viewed as an economically measurable variable: the consumer's willingness to pay for that item.

Utility is not a static concept. It can increase or decrease in response to short-term changes in market prices and availability, and to long-term changes in lifestyle, tastes, expectations, technology, and population demographics. Utility also can be increased or decreased with change in system reliability, or service quality.

For the analysis to follow, utility is assumed to be a subjective measure of customer's satisfaction from any consumption of a goods or service. It is further

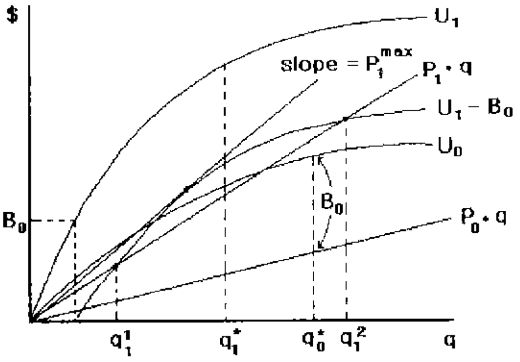

Fig. 1. Utility Function.

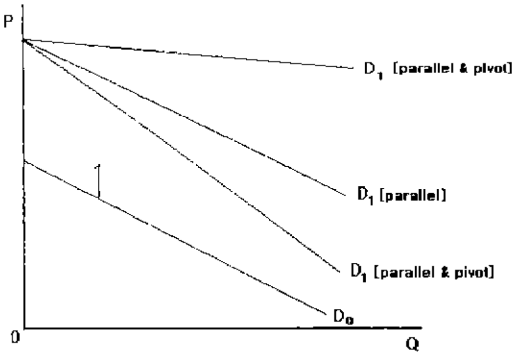

Fig. 2. Types of Demand Shift.

assumed that utility is price free, and is subjected to vary only with the quantity consumed, and quality served. That is, holding quantity fixed, utility varies with the quality of service being served, or vice versa.

Figure 1 explains an idea of the use of utility function in the pricing scheme. In the figure, q_o is the optimal demand of a customer whose utility function is U_o at the price p_o, and yields net benefit Bo. For any customer having U_l (r_l), any price below p^* finds q's yielding a net benefit greater than B^o. For instance, at p_1, the open set (q_1^1, q_1^2) gives net benefit greater than B_o by purchasing additional quality, i.e., purchasing the uprated service, r_1, where p_1^{max} denotes the maximum price level that the regulator(or the producer) can exercise for the service r_1. In this case, the regulator would set the price so that it maximizes the net social benefit. This enables the producer to enhance the flexibility in pricing.

3-2. The Effects of Quality Differentiation[16]

Suppose that the service quality can be denoted by some numerical level r, and that both utility and costs depend on service quality. Then the social welfare function with consumption of q will be.

$$W(q, r)=U(q, r)-C(q, r). \tag{1}$$

Assume that quality is a good, so that $\partial U/\partial r>0$, and that it is costly to produce, so that $\partial C/\partial r>0$. Both the electric utility and customer maximize net benefits:

$$\text{(Electric utility)} \quad \underset{q,\,r}{\text{Max}}: \Pi=p(q, r)\, q-C(q, r) \tag{2}$$

$$\text{(Customer)} \quad \underset{q\ r}{\text{Max}}: B=U(q, r)-p(q, r)\, q \tag{3}$$

From the derivatives of the welfare function at the optimum (q, r), and the first order conditions for the maximization problems, we get the following relationships.

$$\frac{\partial W(q,r)}{\partial q}=-\frac{\partial p(q,r)}{\partial q}q \tag{4a}$$

$$\frac{\partial W(q,r)}{\partial r}=\frac{\partial U(q,r)}{\partial r}-\frac{\partial p(q,r)}{\partial r}q=\frac{\partial B}{\partial r} \tag{4b}$$

where, $\frac{\partial p}{\partial r}q$ =marginal cost of producing more quality.

The first equation tells that, holding quality fixed, the firm produces too little output (due to shortage of supply), relative to the social optimum. The second equation represents the relationship between welfare and service quality. For instance, in Fig. 2,when service quality increases, the demand curve shifts up, and possibly tilts one way or the other. Decompose this movement into a 'parallel' shift up and a 'pivot' as indicated. Consumer' surplus is unaffected by the parallel shift, so the total change depends on whether the inverse demand curve becomes flatter or steeper. Equation (4a) holds positive always. In case of shortage, the marginal cost of producing service quality is definitely zero, so the equation (4b) becomes also positive.

3-3. Pricing Mechanism

The pricing scheme proposed here is a combined form of self-selecting tariff and conventional real-time pricing scheme, with diversified service quality. We solve the following social welfare maximization problem with constraints, including Break-even condition, Non-crossing demand condition, Individual Rationality condition (IR), and Incentive Compatibility condition (IC):

$$\underset{r,q,p}{\text{Max:}} \sum_{i=1}^{n} k_i CS_i \tag{5}$$

where, n denotes total number of consumers, k_i weighting factor, (r. q, p) is choice space of quality, quantity, and price, respectively. For the convenience of analysis, it is assumed that individual customers' utility functions are quasilinear and concave (to remove the income effect in the analysis).

The above equation can be explained in another way. Let U_{ij} be the utility function for customer i's use of electricity at any time, under the chosen service level, r_j. Then the customer will choose an optimal set of service $\{(q_{ij}, p_j)\}$ over the service quality r_j to maximize his net benefit by the Eq. (3). At the same time, producer must set the p_j's optimally according to customer' valuation of service, U_{ij}, with the service quality, r_j.

3-3-1. Pricing in case of Scarce Capacity[17]

This section examines how efficiently the new pricing scheme can be applied when the system experiences a shortage of supply and needs to cut off part of its demand temporarily.

Now consider the case when there is a shortage of supply. Any outage due to scarce of supply causes a loss of customer benefit, and some times, accompanies an outage cost. Our primary concern lies in short-run consumer behavior under diversified service quality.

Consider Fig 3, which depicts the demand curves of a customer facing two service levels, r_0 and r_1, where E_0 is the equilibrium point at the service level, r_0 (For simplicity, the demand curves are assumed to be linear without loss of generality.) The demand curve D (r_0) represents directly the level of the consumer' WTP for higher service level, r_1. In this case, the demand q_1 is determined by the equation (3).

For any customer having the inverse demand curve, D (r_0), the area 'abEo' represents the loss of consumer benefit when supply is cut back to q_1. Additionally, some outage cost also can be expected. In this case, our concern is whether the consumer will be willing to pay more than the current charge for continued service.

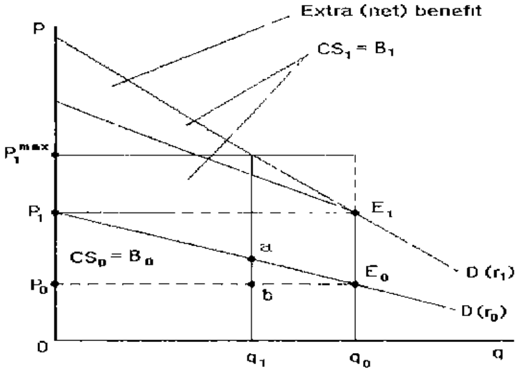

Fig. 3. Change in Consumer Surplus.

It is noted first before reasoning the answer that D (r_0) represents the consumer' maximum WTP for the electricity at service quality, r_0. Since the customer is generally assumed to be a rational benefit maximizer, he must recognize the meaning of service quality he has chosen. In other words, the customer fully understands the consequences of service interruption, if any, so the inverse demand curve reflects the customer' real WTP for the service. That is the 'expected outage cost' has already been reflected into the demand curve, and this should not change the consumer's behavior because this choice is optimal for the consumer; otherwise he would not have chosen the service quality r_0.

Then, what if the customer wants to pay more to avoid outage, and what is the optimal price in this case? This can be interpreted as that the customer wants an upgraded service quality, he must behave along D (q: r_1) in the Fig. 3.

In this case, holding the quantity fixed, the price, p_1, that the customer is willing to pay for the (continued) service can be given as,

$$p^1 = p^0 + \frac{1}{q_0}(r^1 - r^0)\frac{\partial U}{\partial r} - \frac{1}{q_0}(B_1 - B_0) \tag{6}$$

where, $\frac{\partial U}{\partial r}$ =marginal value of service at r_0,

$(r^1 - r^0)\frac{\partial U}{\partial r}$ =gain with change in service quality,

B_0=net consumer benefit from r_0,

B_1=net consumer benefit from r_1.

The firm therefore can set the price as,

$$P_0 \le P_1 \le P_1^{max} \qquad (7)$$

where P_1^{max} is the maximum price the electric utility can set. (In this case. the customer' net benefit. B_1, is equal to his previous benefit of B_0).

Customer who behaves along the inverse demand curve D (r_1) reveals that his service valuation is relatively high. In other words, if there were only a single service standard which is inferior to r_1, then this customer would lose some of his potential benefits, which could otherwise be attainable under the service level, r_1. Therefore, whoever prefers r_1 to r_0 will be willing to pay more for *sure*. or *enhanced* service, even without any change in his consumption pattern. This explains the consumer behavior in short-run, or very short-run.

3-3-2. Revenue Reconciliation[18]

Since electricity producers are regulated monopolies, a necessary consideration in the implementation of RTP is reconciling the revenue that would be earned under real-time prices with the overall revenue requirements constraint of the firm. With real-time prices, one would not automatically expect that the overall revenue earned will equal what would have been earned with conventional prices set according to conventional regulatory cost-of-service criteria. Some adjustment may be necessary to raise or lower the overall level of prices so that too high or too low overall rates of return do not result. Alternatives for reconciling the real-time prices are discussed in[18].

With the proposed pricing scheme, the welfare gain of an individual customer i due to change in service quality can be estimated as,

$$\triangle CSi = \sum_{j=1}^{m} \int_{q_{j-1}}^{q_j} D_i^{-1}(q; r_j)dq - \int_0^{q} D_i^{-1}(q; r_0)dq$$

where. q_i=optimal demand

$D_i^{-1}(r_j)$=inverse demand function of customer i under service quality, r_j

m=number of service quality

The revenue to be reconciled, R. is therefore given as,

$$R = C_t - \sum_i \alpha_i \triangle CS_i \qquad (9)$$

where, C_f=total fixed cost of the utility

α_i=transfer rate of $\triangle CS_i$ from customer i to the firm

$1 \ge \alpha_i \ge 0$

The rate maker finds optimal α_i, which is determined implicitly as a consequence of exercising the pricing scheme in Section 3.1, to recover the utility's cost.

4. Conclusion and Future Study

The purpose of this paper is to propose an efficient real-time based pricing scheme which maximizes social welfare by diversifying service quality under imperfect information on consumers' purchasing behavior.

Among the possible advantages of the proposed pricing scheme are; 1) it adopts the utility function as a measure of customers' perceived value of service received. This enables the electric utilities to provide customers with accurate price signals, as well as handle the problems of pricing, investment decision. and demand side management consistently, 2) it can satisfy the important requirement that the tariff design must not disadvantage any customer, in that it has the customers charged differently based only on their revealed valuations of service. 3) it can provide the electric utilities with more flexibility in operating their systems when a shortage of supply encountered, without any loss of social welfare, 4) with the information on individual customer' or group' utility function over diversified service quality. it can be implemented without resort to frequent auction which is necessary in conventional priority pricing.

The last two advantages imply that the proposed pricing scheme can be applied to direct load control (DLC) on a real-time basis subject to proper communication infrastructure.

Finally. in the pricing scheme proposed here, the transmission congestion charge and generation curtailment premium. which might be necessary in conventional real time pricing, may not be valid any longer[19].

In order for the proposed value-based pricing to be an efficient and appropriate pricing policy. it would be better that the distribution of the customer needs and preference with regard to service quality and reliability should be assessed well, and the fact that the development of the pricing scheme is not unfairly discriminatory must be ensured.

With this, much work will be devoted to the following issues. 1) How the quality of electric service can be diversified, 2) What are the alternative techniques for estimating customer utility functions that could be used to stabilize customer price-value relationships, 3) How this pricing scheme can be implemented on a real-time basis, 4) How might this pricing scheme be adapted in system reliability applications, and investment decision.

Finally, a study on application of the pricing scheme to real systems should be carried out to verify the practicability and efficiency of the proposed pricing mechanism.

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