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Effect of demand management on regulated and deregulated electricity sectors

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HIGHLIGHTS

- Demand management can help prevent forced electricity outages.
- Both electric utilities and ISOs can use demand management.
- Regulated and deregulated electricity sectors can benefit from demand management.
- Demand management contracts can be effectively used in power system grids.

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ABSTRACT

Our society derives a quantifiable benefit from electric power. In particular, forced outages or blackouts have enormous consequences on society, one of which is loss of economic surplus. The society relies on having a continuous supply of electrical energy. Some customers may willingly risk this continuous supply and participate in demand management programs for electrical power. If the power system grid is in trouble, electric utilities need to have demand relief. Customers willing to reduce their demand to help the system can receive an incentive fee for helping the utilities. Demand relief can be system wide or location specific. Sometimes it can be more effective to fix the electrical demand vs. supply imbalance from the demand side. The value of demand management contracts is greatly affected by customer location. Inclusion of locational attributes into the contract design procedure increases the effectiveness of the contracts by helping a utility get more value from its demand management programs. Independent System Operators and regulators, among others, can also benefit from effective demand management. This paper will investigate how this type of demand management contracts can help the electricity sector both in regulated and deregulated environments.

1. Introduction

A reliable electrical power system needs to have adjustable loads during stressful times of the system. Hence this paper assumes voluntary involvement to demand management programs where customers receive compensation for participation. The incentives the customers receive play a critical role in demand side management. Outage costs of customers need to be accounted for properly in order to optimize the offered incentives. In order to design such contracts, optimal mechanism design with revelation principle is adopted from **"**Game Theory**"** and applied to the interaction between an electric utility and its customers (Fahrioglu and Alvarado, 2000). Authors in (Fahrioglu and Alvarado, 2000) explain the idea behind mechanism design and how it is used to design an incentive structure that encourages customers to sign up for the right contract and reveal their true value of power (and thus, the value of power interruptibility). Demand management programs (Rahman and Rinaldy, 1992), Violette et al. (1991), (Gellings, 1985) can help mitigate electrical system problems. Location plays an important role in demand management of a power system grid. Demand management contracts with customers at sensitive locations can solve problems more efficiently. Locational attributes need to be a big part of this type of demand management. The benefits of the contracts designed using Game Theory exceed the benefits of existing demand management contracts for the electric utilities, and in most cases their customers. Some customers receive more incentives and the electric utilities get more monetary benefit and more contracts at critical locations of the power grid. Incorporating locational flexibility into the

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demand management contracts enables utilities to extract maximum value from their demand management programs. The contracts designed in (Fahrioglu and Alvarado, 2000) are "pay per incident" contracts. This approach to demand management is likely to prove more useful than the traditional "lower rates" interruptible contract approach because it more clearly lines up the interests of diverse customer types with diverse locational electricity utility needs. These kinds of demand management contracts can also be used by an Independent System Operator (ISO) which is in charge of the power system grid in a deregulated electricity sector where we have an open market to produce electric power. The main job of an ISO is to maintain a reliable grid in the interests of all buyers and sellers of electricity. Hence it is the ISO's responsibility to avoid congestion and keep the "Available Transfer Capacity" (ATC) at a high level. During times of congestion a loss of economic surplus occurs. To relieve congestion, ISOs will have a choice between congestion pricing, mandatory Transmission Load Relief or the use of interruptible power contracts. Interruptible power contracts are "standing" offers for power "delivery" at a given price. Hence interruptible customers participate in a spot market by designating their power as interruptible. The idea is that the power market itself should resolve congestion issues. However when the market is too slow or cannot help relieve congestion, demand management can help solve the problem. With fast developing smart grids for power systems, demand management will become an even more powerful tool (Saffre and Gedge, 2010), Xudong et al., (2010). Authors in (Chapman and Tramutola, 1989) talk about the real time pricing of demand side management which shows that the demand side can compete with the supply side in different environments. Expansion in the electricity sector is inevitable, however this paper will show that demand side management can help delay this expansion as much as possible. A. Lovins was one of the first advocates of demand side management (Lovins, 1985); he showed how curtailing the demand can save the system a lot of money.

2. Demand management contracts using mechanism design

Mechanism design and the revelation principle (Fudenberg and Tirole, 1991) (Kreps, 1990) are key concepts used in nonlinear pricing. Mechanism design can help the electric utility, having no cost information about its customers, design optimal contracts to buy interruptible power from the customers (Fahrioglu and Alvarado, 2000). The mechanism will produce the amount of interruptible power for each customer and its price for the electric utility. The utility develops an optimal incentive function to indicate how much it is willing to pay for a given amount of curtailment, and the customers self-select the amount of curtailment based on an inspection of the incentive function offered to them. A general formulation is developed in this section.

2.1. Electric utility-customer setup

The utility does not know the willingness of its customers to shed power if offered an incentive. Each customer would value the interrupted power differently depending on how much it would cost them to shed load. The utility could simply ask the customers how much their interruption costs are, but they will not report it correctly unless they are given an incentive to do so. The utility can design an incentive scheme that determines the monetary transfer received by each customer as a function of the amount of power they are willing to curtail. The customer's willingness to curtail is modeled by a variable $\theta \in [0,1]$ called the customer's *type*. Assume a utility is buying x kW of contracted curtailable power from its customers. We characterize customers' preference for curtailment probabilistically, through a random variable θ as described above. This "preference parameter" θ possesses a probability distribution $f(\theta)$ over [0,1], and let $F(\theta) = \int_0^{\theta} f(\tilde{\theta})d\tilde{\theta}$. The value of θ is private information of the customer, and is unknown to the utility, $c(x, \theta)$ is the assumed cost of curtailing x kW for a customer with preference parameter θ. $c(x, \theta)$ needs to be non-negative for all θ and x, and $c(x, \theta)$ needs to be nondecreasing in x. The utility is paying y amount of money to the customer willing to shed x amount of power. Hence, the customer benefit function is:

$$u_1(x, y, \theta) = y - c(x, \theta) \tag{1}$$

Under stressed conditions it is expensive for the electric utility to deliver power to certain locations. The utility can compute the value $V_0(x, \lambda)$ of *not* delivering power to a certain customer, where λ is the incremental benefit of not delivering power to a certain location in the network. Then the utility profit from this power curtailment of a customer is:

$$u_0(x, y, \lambda) = V_0(x, \lambda) - y \tag{2}$$

Having a subjective estimate of the customer types it is dealing with, the utility develops an incentive function $Y(x)$ to indicate how much it is willing to pay someone for a given x amount of curtailment, and develops a function $X(\theta, \lambda)$ for how much it thinks a customer of type θ at location λ should curtail. Customers self-select the amount of curtailment they wish to be subjected to, based on an inspection of the incentive function offered to them. They are assumed to do so rationally, by making the amount of compensation they receive from participation match the monetary incentive offered by the electric utility minus the actual net loss of benefit that result from the curtailment. Customers will not choose to be curtailed unless they see a net positive benefit. Thus it is necessary that the customer benefit $u_1(X(\theta, \lambda), Y(X(\theta, \lambda)), \theta) \geq 0$.

2.2. Customized game theory optimization

The customer benefit function (1) needs to satisfy the necessary *sorting condition* (Chapman and Tramutola, 1989); $\frac{\partial u_1}{\partial y}>0$ and $\frac{-\partial u_1 / \partial x}{\partial u_1 / \partial y}$ should be decreasing in θ. In the case of Eq. (1) since $\frac{\partial u_1}{\partial y}=1$ the sorting condition reduces to $\frac{\partial c}{\partial x}$ being decreasing in θ which simply provides a way of "sorting" the customers from least willing to most willing to curtail load, i.e. the customer with the highest marginal cost (and hence the lowest marginal benefit) has the lowest value of θ. The goal is to maximize expected profit for the electric utility.

$$\max_{X(.),Y(.)} E_{\theta} u_0(X(\theta, \lambda), Y(X(\theta, \lambda)), \lambda) \tag{3}$$

subject to (for each customer with its locational value λ),

$$u_1(X(\theta, \lambda), Y(X(\theta, \lambda)), \theta) \geq 0 \tag{4}$$

$$u_1(X(\theta, \lambda), Y(X(\theta, \lambda)), \theta) \geq u_1(X(\hat{\theta}, \lambda), Y(X(\hat{\theta}, \lambda)), \theta) \tag{5}$$

for all θ and $\hat{\theta}$, where $\hat{\theta}$ is the preference parameter of a customer if they were to report it incorrectly. If a customer picks any of the contracts that is not specifically designed for them (the mechanism designs a specific contract for each type of customer, i.e. for each value of θ), they pose as another type of customer ($\hat{\theta}$). Constraint (4) is the *individual rationality constraint* which makes sure every customer is encouraged to participate, and constraint (5) is the *incentive compatibility constraint* which encourages the customers to tell the truth about their θ (i.e. choose the contract designed specifically for them). In applying the incentive compatibility constraint each customer is checked with its fixed value