Pricing Mechanism for Electricity Demand Management to optimize Operation of Power Supply Systems

Natalia Aizenberg
Melentiev Energy Systems Institute SB RAS
Irkutsk, Russia
aizenberg.nata@gmail.com

Elena Stashkevich
Irkutsk National Research Technical University
Irkutsk, Russia
evstashkevich@yandex.ru

Abstract **— In recent years, the possibility of optimizing the consumer demand to improve the operation of power supply systems has been actively discussed. The paper considers a game-theoretic mechanism for the interaction of a power supply company and several types of electricity consumers. We study how energy consumption can be optimized taking into account the interaction of all the parties. The result of our research is the pricing mechanism which stimulates consumers to optimize their load, i.e. to decrease the peak power relative to the average power during the day. We also consider the possibility of decreasing the risks of power shortage.**

Index Terms **— retail electricity market, load optimization, power shortage, adverse selection model, consumer with bounded rationality.**

I. Introduction

Consideration is given to the problem of the load-controlled consumer that optimizes load by decreasing their demand at peak hours and increasing it at the other time [1]. Power supply company (retailer) being a seller is interested in the active behavior of the consumer because of a potential power shortage at peak hours, which will require high costs to eliminate it.

Our goal is to optimize energy consumption, subject to the interests of all parties. In other words, we are looking for the Nash equilibrium among the interacting economic agents, in which the system of stimuli for the load optimization by consumers them selves is implemented, and the benefit of the power supply company lies in a decrease in the risks of power shortage. The interest of power supply companies is to maximize their profit. The goal of consumer is to maximize the utility from energy consumption. The latter can be evaluated on the basis of the loss function respect to consumption. The formation of such functions is one of the key issues of our research.

Normally, power supply companies render services to several types of consumers with different utility functions (benefits from used electricity). They can be divided into several groups depending on the required electricity supply reliability (according to the rules we will follow, there are three categories of loads). Interests of all types of consumers are related to the electricity purchase cost minimization and to the electricity supply quality and reliability.

Our objective is to form a mechanism capable, by using only market instruments, to maximize the profit of power supply company (in this case it is a monopolist) provided the types of consumers and their interests in their load curve optimization are differentiated which increases payoff of the active participation in the proposed scheme.

The idea of influencing load-controlled consumers is described in a number of papers. The authors of [2] for example describe a game oriented to the load optimization by consumer themselves. The consumer is not obliged to disclose information on their load to the company and other consumers, and the company by solving the discussed problem can offer stimulating tariffs. Moreover, in the course of the problem solving the sources of saving for consumer are determined. Some authors study the situation where the prices are determined in advance and in these conditions consumer actively changes the load in order to economize to the greatest extent possible [3,4]. There are two-level statements of the problem which consider vertically-integrated interactions of a generating company, a retailer, a network and a consumer [5]. In these statements the consumer is represented in an aggregate form, without division into types. There can be statements where the consumers supply surplus electricity to the network [6]. Our problem does not deal with additional generation, i.e. consumers can only shift load from the peak time through a change in their production process, in particular by using the electricity storage systems or by automating the production process. Such schemes are considered in [7].

II. An adverse Selection model

There are several types of consumers. The type is determined by a load category (the degree of required reliability): the first, the second, and the third. Within each category it is possible to split into several groups more. Denote by θ_i the consumer type, $i=\overline{1,n}$ is their quantity. The tariff is assigned according to the load at a certain hour of the day q_t^{θ}, $R_t^{\theta_i}$ is a tariff value at hour t, $t\in[1,24]$ for type θ_i. Each consumer derives some utility from receiving a certain amount of electricity. Denote this utility through the function $u^{\theta_i}(q_t^{\theta_i})$. We will assume that there is always some basic tariff which can be, for example, linear in the time of the day $R_L^{\theta_i}$. This tariff will determine some alternative utility which will be derived by a consumer without participating in the selection of an optimal consumption pattern. Denote this tariff by some value

$$\overline{U}^{\theta_i}=u^{\theta_i}\left(\sum_{t=1}^{24}q_t^{\theta_i}\right)-R_L^{\theta_i}.$$

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The general problem can be formulated as follows.

$$\begin{cases} \pi = \sum_{i-1}^{n}\sum_{t=1}^{24}\left(R_t^{\theta_i} - C\left(q_t^{\theta_i}\right)\right) \to \max_{R_t^{\theta_i} q_t^{\theta_i}}; \\ \sum_{t=1}^{24}\left(u^{\theta_i}\left(q_t^{\theta_i}\right) - R_t^{\theta_i}\right) \geq \overline{U}, \quad i \in [1,n].; \\ \sum_{t=1}^{24}\left(u^{\theta_i}\left(q_t^{\theta_i}\right) - R_t^{\theta_i}\right) \geq \sum_{t=1}^{24}\left(u^{\theta_i}\left(q_t^{\theta_j}\right) - R_t^{\theta_j}\right), \quad i, j \in [1,n]. \end{cases} \quad (1)$$

where $C\left(q_t^{\theta_i}\right)$ - cost to serve the i -th consumer.

III. Model of load optimization for rational consumers

We solve the problem of profit maximization power supply company with the participation of the rational consumer. Condition of participation is described by the constraints that include the conditions of a positive utility in selecting the tariff. In our study we believe that such a consumer can use a two-part tariff. The optimality depends on several factors, including the transparency of such a scheme of payment for consumers and regulators. Here it is assumed that the unit price of electricity corresponds to the marginal cost of a unit of electricity, and fixed costs are covered through an entrance fee (or fee peak power). The government should regulate the entrance fee because in the absence of constraints, the monopolist can confiscate the full consumer surplus, the value of which may exceed the fixed costs of power supply company.

The profit of power supply company can be written as

$$\pi = R^{\theta_i} - C\left(\sum_{t=1}^{24}\left(q_t^{\theta_i}\right)\right) \to \max_{R^{\theta_i}},$$

condition of participation of the consumer

$$-R^{\theta_i} \leq \overline{U}.$$

By accepting the immutability of the consumer's load by virtue of rationality, we find that power supply company will increase the tariff (in this case the entrance fee) until the output on the restriction. A linear tariff is based on the principle of constant income from sales that guarantees normal profit and the covering of fixed costs. Thus the solution gives the following equation:

$$\overline{U} = A^{peak} + \sum_{t=1}^{24} T_t^{\theta_i} q_t^{\theta_i}.$$

IV. Model of load optimization for consumers with bounded rationality

The model is based on the approaches presented in [5]. Let the purchase price for a retailer in the spot market be P_t^S, where t - defines the purchase area, P_t^B - price in the balancing market. x - a potential scope of load optimization by consumer (in this case we consider the volume of load shift from the peak time to the night time). Then the payoff of the power supply company from the load shift can be written in the following form:

$$\pi(x) = \left(P_{III}^B - P_I^S\right) \cdot x - \eta \cdot x,$$

where η - difference in tariffs T_t which are established by the retail company at different times of the day. For simplicity we can assume $\eta = T_I - T_{III}$. Here we represent a cost function of power shortage in a simplified form. The function takes into account only the price difference in the balancing and spot markets. There can be additional costs not related to the price difference, to eliminate the shortage.

Let us consider the consumer costs related to the load shift as some function of the load to be optimized $f(x)$, $f(x) \in C^2$. Here, we suppose that some load will be shifted by consumer without any special efforts. For example, this may concern the use of washing and dishwashing machines. At the same time, there is a load whose shift can cause greater inconveniences, for example, a shift of the food cooking time or additional installation of energy saving equipment. The function $f(x)$ reflects an extent to which the consumer is ready to such costs. The total payoff of the consumer will be represented as

$$u(x) = \eta \cdot x - f(x) \to \max_x. \quad (2)$$

Consumer determines the load to be shifted in the course of maximizing their payoff $u(x)$.

Let the function of costs be a convex function with respect to x. To find the Nash equilibrium and match the interests of all the stakeholders it is necessary to find a point at which the maximum profit is reached for the power supply company and the maximum payoff - for the consumer:

$$\left(P_I^B - P_{III}^S\right) \cdot x - \eta \cdot x \to \max_\eta;$$

$$\eta = f'(x),$$

$$x \geq 0, \;\; \eta \geq 0.$$

The conditions mean that the consumer will shift a certain load at different tariff difference η:

$$\left(P_I^B - P_{III}^S\right) \cdot \left(f'\right)^{-1}(\eta) - \eta \cdot \left(f'\right)^{-1}(\eta) \to \max_\eta, \;\; \eta \geq 0. \quad (3)$$

By solving this problem we will determine all the necessary characteristics of the equilibrium.

Let us take for an example the function which can describe potential consumer expenses caused by the load shift. The measurement units can be represented by money units, but we assume that this is an equivalent to the consumer efforts to change their load curves.

$$f(x) = -\beta \cdot \log\left(\frac{\alpha - x}{\alpha}\right). \quad (4)$$

Figure 1 presents such a function at $\beta = 3{,}38$, $\alpha = 360$. These parameters were determined using the real data on the consumer load curves. Each of the parameters can be interpreted in a certain way. Parameter α (asymptote) is a maximum possible load to be shifted by the consumer from the peak time.

Parameter β controls the level of costs according to some money equivalent. In this paper this index is estimated on the basis of empiric data on the possibilities of load change in the considered categories of consumers.

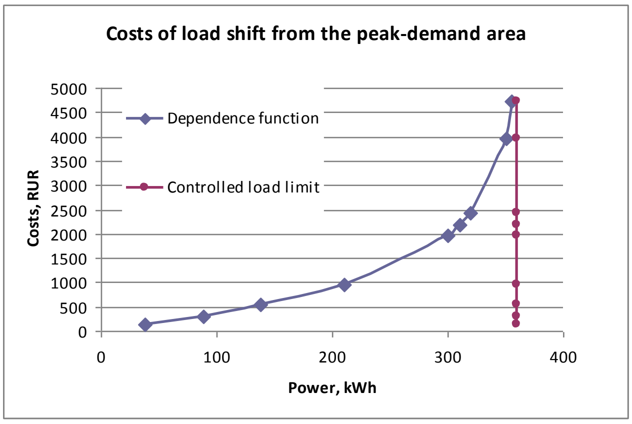

Figure 1. Estimation of the potential consumer costs at the load curve optimization (4).

Further, we will write the utility function of the consumer (2)

$$u(x) = \eta \cdot x + \beta \cdot \log\left(\frac{\alpha - x}{\alpha}\right) \qquad (2^*)$$

and determine x .

$$x = \alpha - \frac{\beta}{\eta}.$$

Thus we can see that the larger the tariff difference the greater the wish to change the load curve. Further, substitute x in (3).

$$u(\eta) = \left(P_I^B - P_{III}^S\right) \cdot \left(\alpha - \frac{\beta}{\eta}\right) - \eta \cdot \left(\alpha - \frac{\beta}{\eta}\right) \to \max_{\eta} .$$

$$\eta = \sqrt{\frac{\beta\left(P_I^B - P_{III}^S\right)}{\alpha}} .$$

V. Solving the Problem on the Differentiation of Consumer Types and Determination of an Optimal Tariff

Write the conditions of participation:

$$-\left(A^{peak} + \sum_{t=1}^{24} T_t^{\theta_1} q_t^{\theta_1}\right) \geq T^L \sum_{t=1}^{24} q_t^{\theta_1} , \qquad (5)$$

$$-\left(T_{III} + \eta\right) \cdot \left(\sum_{t \in I} q_t^{\theta_2} - x\right) - T_{II} \cdot \sum_{t \in II} q_t^{\theta_2} -$$

$$- T_{III} \cdot \left(\sum_{t \in III} q_t^{\theta_2} + x\right) \geq T^L \sum_{t=1}^{24} q_t^{\theta_2} \qquad (6)$$

In the relationships, T^L means a basic linear tariff. I, II, III are sets of hours corresponding to a certain tariffing zone. The individual rationality constraints for consumer types, which mean that the selection of "their" tariff proves more beneficial than the selection of a tariff of another consumer type.

$$-\left(A_{peak}^{\theta_1} + \sum_{t=1}^{24} T_t^{\theta_1} q_t^{\theta_1}\right) \geq - \sum_{t \in \{I,II,III\}} T_t \cdot q_t^{\theta_1} , \qquad (7)$$

$$-\left(T_{III} + \eta\right) \cdot \left(\sum_{t \in I} q_t^{\theta_2} - x\right) - T_{II} \cdot \sum_{t \in II} q_t^{\theta_2} -$$

$$- T_{III} \cdot \left(\sum_{t \in III} q_t^{\theta_2} + x\right) \geq -\left(A_{peak}^{\theta_2} + \sum_{t=1}^{24} T_t \, q_t^{\theta_2}\right) \qquad (8)$$

Here, we do not consider the variant, where the type of consumer with bounded rationality chooses a two-rate tariff, but at the same time shifts its load, since in this case the statement of the problem changes. Our objective is to encourage only the consumers with bounded rationality to optimize their load curve. If the consumer can optimize their load curve without an additional action from the power supply company, it refers to the rational type θ_1 .

The function of the power supply company profit is concave.

$$\gamma \cdot R^{\theta_1} + (1-\gamma) \cdot R^{\theta_2} - C\left(\sum_{t=1}^{24}\left(q_t^{\theta_1} + q_t^{\theta_2}\right)\right) \to \max_{R^{\theta_1}, R^{\theta_2}} , \qquad (9)$$

where $C\left(\sum_{t=1}^{24}\left(q_t^{\theta_1} + q_t^{\theta_1}\right)\right)$ is the total costs of the power supply company's power purchase in the market and its delivery to the consumer.

By solving the problem of power supply company profit maximization (9) under constraints (5)-(8) we will obtain the equilibrium represented by optimal tariffs of an offer, which reconcile the interests of different types of consumers and supplier.

VI. Analysis of Electricity Tariffs Currently Used in a District of Irkutsk

In our case study the whole set of consumers that form the load curve of a power system will be represented by the consumers of an Irkutsk district (students' area). The main consumers of electricity are loads of hostels, educational buildings, student's catering facilities, municipal health center and prophylactic sanatorium.

In this case, the health center and prophylactic sanatorium are electric loads belonging to the category which requires more reliable electricity supply (denoted by Roman numeral III in Fig 2). According to the ideas of a retailer, they should choose a two-rate tariff with a large payment for connection (power) and a non-differentiated small payment per unit of electricity. Another group (hostels, educational buildings and students' catering facilities - in the Figure denoted by II) on the contrary, should choose a differentiated tariff per electricity unit at a zero rate for power. Such tariffs are profitable for consumers and are formed in the first stage of the problem solving, which suggests that the company operates only for one type of consumers with a tariff type determined in advance.

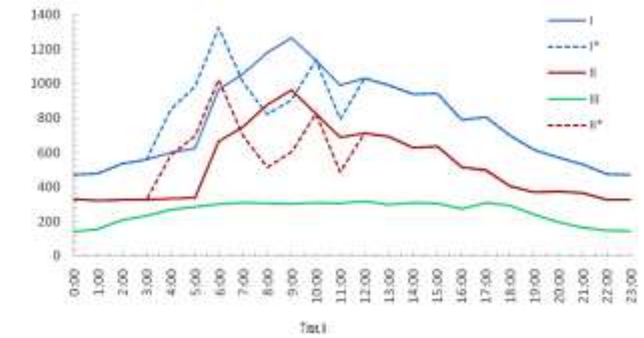

Fig.2 A generalized daily load curve of the power supply company before load shift (1), after load shift (1*), and consumers which form this load curve: consumers of the third category before load shift (II) and after load shift (II*), and the consumers of the second category (III).

In the second stage, the type of consumers that can be interested in choosing “not their tariff” is determined. Further, the main problem (9) is solved. The conditions for the mixed equilibrium and for the equilibrium differentiating the types are found.

VII. RESULTS OF THE STUDIES

The technique of the tariff menu formation is suggested to optimize the pattern of electricity supply to different types of consumers. The power supply company is either a monopolist or a regulated monopolist.

A possible variant of the tariff menu is developed for electricity supply to an individual area in Irkutsk. The types of consumers are defined and differentiated, the utility functions for them are formed. The utility functions describe well the reality and make it possible to implement the system of stimuli for the load optimization (in this case, a load shift from peak to off-peak time by the consumers with bounded rationality of preferences). The tariffs providing the differentiating equilibrium are found. The tariff menu approved legislatively is tested [8]. The potential inefficiency of the existing scheme is shown. The difference in the steps for the differentiated tariff is too large, and therefore the tariff is rejected by consumers with bounded rationality in favor of a two-rate tariff which suggests sparing conditions. The latter is unprofitable for the power supply company, since if part of load is not shifted from peak time, the shortage appears and the company’s costs related to this shortage increase greatly.

In the research we have adjusted the differentiated tariff on the basis of the presented methods, and brought to the correspondence the system of stimuli for load optimization which will reduce the probability of shortage to the minimum.

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