System aspects of price responsive energy consumption

V I Kolesov, G A Hmara and A L Portnyagin
Industrial University of Tyumen, 38 Volodarskogo st., Tyumen, 625000, Russia
E-mail: hmaraga@tyuiu.ru

Abstract: The article is focused on the synthesis of decision support systems in the field of Smart Grid. The structural and parametric identification of the model is made for assessing the effectiveness of the decision taken by the consumer to participate in demand management. The results of calculations are presented.

1. Introduction
The introduction of the mechanism of price responsive consumption (PRC), which increases the efficiency of electricity production in the regions and in Russia as a whole, is rapidly progressing. Its essence, as is known, is to maintain a balance of supply and demand in the electricity market both due to changes in the load of generation facilities, and by changing consumption. The abolition of the upper price limit for electricity in the wholesale market for electricity and power (WMEP) in the Russian Federation, scheduled for 2021, changes the principles of interaction between consumers and producers. Now, to manage the price in a deficit, a balanced decision should be taken on the part of consumers. Involvement of consumers in the process of demand management raises new problems for them, related to the adoption of reasonable decisions in the processing of applications. Due to the novelty of the topic, effective tools for consumers in the sphere of decision support (DS) have not been created yet. The task is set, at least partially, to eliminate the existing gap.

2. Research
The formalization of the task is reduced to determining the conditions for making a decision on price responsive consumption. The essence of the solution is to choose the amount of energy consumption reduction during the regional maximum hours by $\Delta V$ (MWh) by switching off a part of consumers $N$ times per month $m$ ($1 \leq N \leq 10$) [1]

$$\Delta V_m = \sum_{N=1}^{10} P_N \cdot T_N,$$  \hspace{1cm} (1)

where $P \geq 2$ MW – power of disconnected consumers; $T$ – shutdown duration: 2, 4, 8 hours per day.

In this case, shutdowns are carried out at the direction of the System Operator (SO UES). In addition to reducing the cost of electricity, a consumer with a PRC receives an additional premium, in the form of a reduction in the cost of capacity, for the assistance of the SO UES in solving system tasks for ensuring a reliable and secure electricity supply to the region.

Today, the interaction between the consumer and the SO UES in the sphere of price responsive consumption is the planning and implementation of joint actions on the impact on power flows in the...
regional energy system. The interaction algorithm is the following: the consumer declares that his readiness for price responsive consumption during the regional maximum hours, indicating the volume, the System Operator accepts the application and schedules the power flows, and the Administrator of the trading system (ATS) of the wholesale electricity market calculates the cost of electricity.

Thus, the cost of electricity in the wholesale market is formed after the decision on price responsive consumption, and consumers have no opportunity to plan their economic activities taking into account the resulting effect from the PRC. Moreover, for enterprises with price responsive consumption, switching off part of the load with a capacity of more than 2 MW can lead to a decrease in productivity and product quality and, as a result, to financial losses not covered by the premium received. That is, there is the problem of deciding on price responsive consumption in the context of uncertainty of the benefits received.

3. Results and discussion

To solve this problem, the authors propose a method of decision support based on the interaction of the supply and demand functions.

The demand model is adopted in the form [1]:

\[ (C_p \cdot V_p)^{m_p} = k_p, \]  \tag{1}

where \( C_p \) - price of service; \( V_p \) - volume of consumption; \( m_p \) - parameter; \( k_p \) - level of quality.

Under the level of quality, we will understand the efficiency of the production process of the consumer in question.

In accordance with (1), the demand function (Fig. 1) is equal to:

\[ C_p = \frac{k_p^{m_p}}{V_p}, \]  \tag{2}

and the volume of consumption

\[ V_p = \frac{k_p^{m_p}}{C_p}, \]  \tag{3}

The supply model is presented as follows:

the supply function is

\[ Cs = k_s \cdot V_s^{m_s}, \]  \tag{4}

and the volume of supply

\[ V_s = \left( \frac{C_s}{k_s} \right)^{1/m_s}. \]  \tag{5}
When the market is in equilibrium (Figure 2), the conditions are met $V_p = V_s = V_0$, $C_p = C_s = C_0$, i.e. 

$$\frac{k_p^{1/m_p}}{C_0} = \left(\frac{C_0}{k_s}\right)^{1/m_s},$$

from which follows

$$C_0 = \left(k_p^{1/m_p} \cdot k_s^{1/m_s}\right)^{m_s/(1+m_s)}. \tag{6}$$

The price responsive energy consumption changes the market equilibrium point from the coordinates $(V_{01}, C_{01})$ to the coordinates $(V_{02}, C_{02})$.

When $m_p = 1$; $m_s = 2$ and $k_s = 0.5$ we obtain $C_0 = 0.5^{1/3} \cdot k_p^{2/3}$. The graph $C_0(k_p)$ is shown in Figure 3.

![Figure 1. Demand function.](image1)

![Figure 2. Market Equilibrium](image2)
The analysis of Figure 3 shows that the reduction in the equilibrium price is achieved by reducing the level of quality $k_p$. How to understand this decline and what really happens?

The decline in quality can be interpreted as reducing the attractiveness of the service to the consumer. In other words, a certain negative increases the difficulty of reaching the consumer's global goal. Indeed, on the one hand, the positive of the situation is to reduce the price for electricity, but on the other - there is an obvious negative, associated with the inability to fully use the energy resource during rush hours.

A way to assess the difficulty of achieving the goal and to parry its progress is offered by a methodology developed by the scientific school of I.B. Russman and his students [2]. It is widely used in the design of complex systems to solve problems of optimizing their effectiveness, taking into account the risk of not reaching their sub-goals with the components of the system. In general, the components of a system can be understood as key performance indicators (KPI), from which the objective function (OF) is constructed, which is a mathematical model of the accepted criterion. KPI, for each specific consumer is determined in accordance with the characteristics of its activities and in this article are not considered in detail.

The key point of the methodology is the introduction of the concept of difficulty of achieving the goal $d_i$ for each $i$-subsystem. It is postulated that each of them has a normative requirement for quality of $\epsilon_i$, while in reality it is equal to $\mu_i$, and then $d_i$ is interpreted as the risk of not reaching the $i$-subsystem of its goal

$$d_i = \frac{\epsilon_i \cdot (1 - \mu_i)}{\mu_i \cdot (1 - \epsilon_i)}, \quad \text{where} \quad \mu_i = \frac{X_{i_{\text{in}}} - X_{i_{\text{min}}}}{X_{i_{\text{max}}} - X_{i_{\text{min}}}}; \quad \epsilon_i = \frac{X_{i_{\text{in}}} - X_{i_{\text{min}}}}{X_{i_{\text{max}}} - X_{i_{\text{min}}}};$$

$X_{i_{\text{in}}}$, $X_{i_{\text{min}}}$, $X_{i_{\text{max}}}$ - the normative, minimum and maximum values of the level of quality.

With this approach, the objective function $D$ (or its information equivalents) is expressed through the so-called qualitative function $F(d_1, d_2, \ldots, d_n)$.

One of the typical functions is a quality function similar to the Cobb-Douglas production function, whose analytical representation is of the form [2].
\[ J( D ) = J( d_o ) \cdot \prod_{i=1}^{n} [ J( d_i ) ]^{\lambda_i} . \]  

where \( J( D ) = \ln \left[ \frac{1}{1-D} \right] ; \quad J( d_i ) = \ln \left[ \frac{1}{1-d_i} \right] ; \)

\[ \lambda_i \text{- weight coefficients corresponding to the normalization condition } \sum_{i=1}^{n} \lambda_i = 1 ; \]

\[ d_o \text{- risk determined by the quality of the resource consumed by the system itself.} \]

4. Conclusion
The engineering formulation of the problem under consideration is as follows. A system is being created to which quality requirements \( E \) are imposed. Real quality levels of \( i \)-subsystems \( \mu_i \) included in it are known. It is required to formulate normative quality levels \( \varepsilon_i \) for each \( i \)-subsystem. Before constructing the objective function, we consider the relation (2). Obviously, the lower the \( d_i \) is, the lower the risk that \( i \)-subsystems will not reach their partial targets is and, consequently, the higher system's efficiency is. Thus, the objective function should be focused on minimizing \( \sum_{i=1}^{n} d_i \), which is equivalent to

\[ \sum_{i=1}^{n} J( d_i ) \rightarrow \min . \]  

with the restriction of the form \( \ln J( D ) = \ln J( d_o ) + \sum_{i=1}^{n} \lambda_i \cdot \ln J( d_i ) . \)

The problem is solved using the Lagrange principle, and the Lagrange function takes the form

\[ \Phi = \sum_{i=1}^{n} J_i + \lambda \cdot \left( \ln J( D ) - \ln J( d_o ) - \sum_{i=1}^{n} \lambda_i \cdot \ln J_i \right) \]

\[ \frac{\partial \Phi}{\partial J_i} = 1 - \frac{\lambda \cdot \lambda_i}{J_i} = 0; \]

\[ \frac{\partial \Phi}{\partial \lambda} = \ln J( D ) - \ln J( d_o ) - \sum_{i=1}^{n} \lambda_i \cdot \ln J_i = 0 \]

From the first equation follows

\[ J_i = \lambda \cdot \lambda_i . \]  

then the second equation takes the form

\[ \ln J( D ) - \ln J( d_o ) - \sum_{i=1}^{n} \lambda_i \cdot [\ln \lambda_i + \ln( \lambda )] = 0 \]

or

\[ \ln J( D ) - \ln J( d_o ) - \sum_{i=1}^{n} \lambda_i \cdot \ln \lambda_i - \sum_{i=1}^{n} \lambda_i \cdot \ln( \lambda ) = 0 , \text{ i.e.} \]

\[ \ln( \lambda ) \cdot \sum_{i=1}^{n} \lambda_i = \ln J( D ) - \ln J( d_o ) - \sum_{i=1}^{n} \lambda_i \cdot \ln \lambda_i , \text{ but } \sum_{i=1}^{n} \lambda_i = 1 , \text{ consequently,} \]
\[
\exp[\ln(\lambda)] = \exp\left[ \ln J(D) - \ln J(d_o) - \sum_{i}^{n} \lambda_i \cdot \ln \lambda_i \right].
\]

It means that
\[
\lambda = \exp\left[ \ln J(D) - \ln J(d_o) - \sum_{i}^{n} \lambda_i \cdot \ln \lambda_i \right]. \tag{11}
\]

According to (10),
\[
J_i = \lambda \cdot \lambda_i = \lambda_i \cdot \exp\left[ \ln J(D) - \ln J(d_o) - \sum_{i}^{n} \lambda_i \cdot \ln \lambda_i \right], \tag{12}
\]

but \( J_i = J(d_i) = \ln \left[ \frac{1}{1-d_i} \right] \), from which it follows that
\[
d_i = 1 - \exp[-J(d_i)]. \tag{13}
\]

On the other hand, \( d_i = \frac{\varepsilon_i \cdot (1 - \mu_i)}{\mu_i \cdot (1 - \varepsilon_i)} \), which allows us to formulate a requirement for the normative quality of the \( i \)-subsystem \( \varepsilon_i \):
\[
\varepsilon_i = \frac{d_i \cdot \mu_i}{d_i \cdot \mu_i + 1 - \mu_i} = \frac{1}{1 + 1/(d_i \cdot \mu_i) - 1/d_i}. \tag{14}
\]

Substitution of (13) into (14) makes it possible to estimate the initial quality requirements for each \( i \)-component of a complex system.

Moreover, the relation (14) can be used to estimate the required quality margin \( k_i = \mu_i / \varepsilon_i \) for each \( i \)-subsystem
\[
k_i = \mu_i / \varepsilon_i = \mu_i \cdot (1 - 1/d_i) + 1/d_i. \tag{15}
\]

The received working algorithms have passed the software testing.

References

[1] Kolesov V I 2006 Structural identification of economic models of the city bus route. Operation of Vehicles and Special Oil and Gas Equipment: Interuniversity Collection of Scientific Papers (Tyumen: Publishing House “Vector Buk”) p 71-80

[2] Kaplinsky A I, Russman I B and Umyvakin V M 1991 Modeling and Algorithmization of Weakly Formalized Problems of Choosing the Best Variants of the System (Voronezh: VSU) 168 p

[3] Appendix 19.9. Regulation of participation in the wholesale market of buyers with price responsive consumption [Electronic resource] Access mode: http://so-ups.ru/index.php?id=dr_doc