Multicriteria Optimization in Load Management and Energy Market Problems

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Abstract: - The problems of power and energy shortage (natural or associated with the economic feasibility of load management) allocation are formulated within the framework of multicriteria optimization models. This allows one to realize a new technology of load management, which provides the consideration and minimization of diverse consequences of power and energy shortage allocation as well as creation of incentive influences for consumers. Analysis of multicriteria models is associated with decision making in a fuzzy environment and is based on solving *maxmin* problems. The results of the paper are of a universal character, applicable to energy market problems and have been realized within the framework of an adaptive interactive decision making system.

Key-Words: - Load Management, Power and Energy Shortage Allocation, Resource Allocation, Multicriteria Optimization, Fuzzy Set Theory, Aggregation Operators, Adaptive Interactive Decision Making System.

1 Introduction

Different conceptions of load management (for example, considered in [1,2]) may be united by the following: elaboration of control actions is performed on the two-stage bases. On the level of energy control centers, optimization of allocating power and/or energy shortages (natural or associated with the economic feasibility of load management) is carried out for different levels of planning and control hierarchy. This allows one to draw up tasks for consumers. On their level, control actions are realized in accordance with these tasks.

Thus, the questions of power and energy shortage allocation play a large role in a family of load management problems. These questions are complex and should be considered from the economical and technological as well as from the social and ecological points of view. Besides, when resolving these questions, it is necessary to account for considerations of creating incentive influences for consumers.

Considering this, it should be noted that methods of power and energy shortage allocation based on fundamental principles of allocating resources have drawbacks. Their overcoming is possible on the basis of formulating and solving the problems within the framework of multicriteria models. This allows one to consider and to minimize diverse consequences of power and energy shortage allocation and to create incentive influences for consumers.

The application of the multicriteria approach to load management permits one to give a new look at problems generated by processes of the electricity industry deregulation and restructuring [3] to fill their statement by new, most likely, more realistic content. In particular, market participants aspire to maximize their benefits (including economical and also technological, social, political, etc. factors). Thus, a criterion for many energy market problems cannot be presented as a unified function. The goals of market participants, as a rule, come in conflict, which may be resolved by search for a compromise. Its objective is to create mutually advantageous and harmonious relations between market participants.

Taking the above into account, the present paper is dedicated to posing and solving problems of power and energy shortage allocation within the framework of multicriteria optimization models. Their analysis is based on using the Bellman-Zadeh approach to decision making in a fuzzy environment. The results of the paper have been realized as an adaptive interactive decision making system (AIDMS).

The use of the results of the paper permits one to improve the validity and efficiency in allocating power and energy shortages. They can serve as a methodological, informational and computational bases for developing load management systems, considering, for example, results of [1,2] for the consumer level. The paper results are also applicable to energy market problems (dispatching strategies, contract market management, transaction congestion management, etc. [3]).

2 Goals of Power and Energy Shortage Allocation and Problem Formulation

When analyzing problems of allocating resources, a control center having an amount of resource B has to allocate it between consumers. This allocation is usually carried out in conditions of incomplete and inauthentic information about real consumer needs, and the center is forced to allocate resource with the assumption that consumer needs $m_i, i = 1,...,n$ are equal to their demands $d_i, i = 1,...,n$.

It is possible to indicate three principles of allocating resources, which are applicable to power and energy shortage allocation [4]: proportional allocation, optimal allocation and principle of inverse priorities.

The use of the principle of proportional allocation leads to a tendency of overstating consumer demands if $\sum_{i=1}^{n} d_i > B$ with ignoring the necessity of minimizing their damage [4].

When using the principle of optimal allocation, such a solution is obtained [4] that provides the minimum of a total consumer damage. However, this principle also leads to overstating consumer demands [4]. Besides, the construction of damage functions is attended by difficulties, and they have essential uncertainty [2]. Finally, the idea of minimizing the total damage by itself may be subjected to questioning because can lead [5] to "taking money from one consumer and putting them into the pocket of another consumer".

The principle of inverse priorities is the artificial one and forces consumers to decrease their demands [4]. This principle, as other principles, does not stimulate consumers to demonstrate objective demands. In addition, the allocation of resources on the basis of the indicated principles does not provide stimulating influences for consumers. Finally, when solving such problems as allocating resources or their shortages, it is necessary to take into account diverse consequences that cannot be reflected within the framework of traditional damage functions.

Overcoming of the noted moments is possible on the basis of formulating the problems within the framework of multicriteria models. Their goals are to reflect diverse consequences (technological, economical, social and ecological) associated with limitation of consumers on the basis of using real, readily available reported and planned information. These models are also to include goals reflecting the need of creating incentive influences for consumers.

Substantial analysis of the problems of power and energy shortage allocation, systems of economics management as well as real, readily available reported and planned information has permitted the construction of a general set of goals to solve these problems in multicriteria statement. The list includes 17 types of goals. Without listing all of them, it is possible to indicate the following goals:

1. Primary limitation of consumer with more low cost of produced production and/or given services on consumed 1 kWh of energy (achievement of a minimal drop in total produced production and/or given services);

4. Primary limitation of consumers with a more low level of payment in the state budget and/or a more low level of lease payment for basic production resources (funds) on consumed 1 kWh of energy;

12. Primary limitation of consumers with a more high level of the coefficient of energy possession of work on consumed 1 kWh of energy (achievement of a maximal drop in the number of workers, whose productivity and, consequently, salary is diminished because of limitations);

13. Primary limitation of consumers with a more high level of pollution of the environment on consumed 1 kWh of energy;

15. Primary limitation of consumers with a more low value of the demand coefficient (primary limitation of consumers with greater possibilities of production out the peak time);

16. Primary limitation of consumers with a more low duration of using maximum load in twenty-four hours (primary limitation of consumers with greater possibilities in transferring maximum load in the twenty-four hours interval).

The general set of goals is sufficiently complete because is directed to decreasing diverse negative consequences for consumers as well as creating incentive influences. This set also is universal because can serve for building models at different hierarchy levels by aggregation of information and posterior decomposition of the problems.

The concrete list of goals can be defined at every case by the decision maker (DM) that may be individual or group.

From the formal standpoint, an achievement of the goals of power and energy shortage allocation is associated with optimizing linear objective functions

$$F_p(X) = \sum_{i=1}^{n} c_{pi} x_i \ . \qquad (1)$$

However, our experience [5] shows that, in some cases, the use of these functions can lead to very "strict" solutions. In this connection it is possible to use objective functions

$$F_p(X) = \sum_{i=1}^{n} \frac{c_{pi} d_{pi}}{d_{pi} - x_i} \qquad (2)$$

to obtain more flexible solutions.

The use of damage functions as the objective functions is associated with minimizing

$$F_p(X) = a_{pi} x_i^2 + b_{pi} x_i \ . \qquad (3)$$

Finally, the consideration of total damage for a group of consumers demands to minimize

$$F_p(X) = \sum_{i=1}^{n} (a_{pi} x_i^2 + b_{pi} x_i) \ . \qquad (4)$$

Taking into account the possibility to apply the objective functions of the types (1)-(4), the problems can be formulated as follows:

$$F_p(x) \to \underset{x \in L}{\text{extr}}, \quad p = 1,...,q \qquad (5)$$

where

$$L = \{x \in R^n \big| 0 \le x_i \le A_i, \sum_{i=1}^{n} x_i = A\} ; \qquad (6)$$

$x = (x_1,...,x_n)$ is the sought for a vector of limitations; A_i is the permissible value of limitation for the ith consumer; A is a total value of limitations for all consumers (taking into account that $A = \sum_{i=1}^{n} d_i - B$).

3 Multicriteria Optimization Problems and Fuzzy Set Theory

The first formal step in solving the problem (5) is associated with determining a set of Pareto optimal solutions $\Omega \subset L$ [6]. Its building is useful for reducing a number of alternatives. However, it does not permit one to obtain unique solutions. It is necessary to choice a particular solution on the basis of additional information of DM. It is possible to classify three approaches to using this information: a priori, a posteriori and adaptive. The most preferable approach is the adaptive one [7].

When analyzing multicriteria problems, it is necessary to solve specific questions of normalizing criteria, selecting principles of optimality and considering priorities (importance) of local criteria. The solution of these questions and development of multicriteria methods are carried out in the following directions: scalarization methods, imposing constraints on criteria, utility theory methods, goal programming and using the principle of guarantee result. Without discussion of these directions (they are considered in [6], for example), it is necessary to point out that one of the most important questions in multicriteria optimization is the quality of obtained solutions. The quality is considered as high if levels of satisfying criteria are equal or close to each other (harmonious solutions). From this point of view, it should be recorded the validity and advisability of the last direction. Other directions may lead to solutions with high levels of satisfying some criteria that is reached by low levels of other criteria [7].

At present much attention is given to rational using information of DM on the basis of the dialog "DM-Computer" with developing interactive systems to solve multicriteria problems. When using the adaptive approach, the procedure of successive improving the solution x^0 is realized as a transition from $x_\alpha^0 \in \Omega \subset L$ to $x_{\alpha+1}^0 \in \Omega \subset L$ with considering information I_α of DM. The solution search may be presented as follows:

$$x_1^0, F(x_1^0) \xrightarrow{I_1} ... \xrightarrow{I_{\alpha-1}} x_\alpha^0, F(x_\alpha^0) \xrightarrow{I_\alpha} ... \xrightarrow{I_{\omega-1}} x_\omega^0, F(x_\omega^0). \qquad (7)$$

A shortcoming of existing interactive systems is associated with their attachment to the sole form of additional information representation. In many cases DM has more spacious information reducing time of the solution search, and, therefore, the development of adaptive interactive decision making systems (AIDMS), allowing to perceive information on a limited language of DM, is important.

The lack of clarity in the concept of "optimal solution" is the basic methodological complexity in solving multicriteria problems. When applying the Bellman-Zadeh approach [8], this concept is defined with reasonable validity: the maximum degree of implementing all goals serves as a criterion of optimality. This conforms to the principle of guarantee result and provides a constructive line in the solution search [7]. Besides, the Bellman-Zadeh approach permits one to realize an effective (from the computational standpoint) as well as rigorous (from the standpoint of obtaining $x^0 \in \Omega \subset L$) method of analyzing multicriteria models. Finally, the approach allows one to preserve a natural measure of uncertainty in decision making and to consider indices, criteria and constraints of qualitative (semantic, contextual) character.

When using the Bellman-Zadeh approach, each of objective functions $F_p(x), x \in L, p = 1,...,q$ of is replaced by a fuzzy objective function or a fuzzy set

$$\tilde{A}_p = \{x, \mu_{A_p}(x)\}, x \in L, p = 1,...,q \quad (8)$$

where $\mu_{A_p}(x)$ is a membership function of $\tilde{A}_p$ [8].

A fuzzy solution $\tilde{D}$ with setting up the fuzzy sets (8) is turned out as a result of their intersection $\tilde{D} = \bigcap_{p=1}^{q} \tilde{A}_p$ with the membership function

$$\mu_D(x) = \mathop{\wedge}_{p=1}^{q} \mu_{A_p}(x) = \min_{p=1,...,q} \mu_{A_p}(x), \quad x \in L. \quad (9)$$

Using (9), it is possible to obtain the solution providing the maximum degree

$$\max \mu_D(x) = \max_{x \in L} \min_{p=1,...,q} \mu_{A_p}(x) \quad (10)$$

of belonging to $\tilde{D}$, and the problem (5) is reduced to

$$x^0 = \arg \max_{x \in L} \min_{p=1,...,q} \mu_{A_p}(x). \quad (11)$$

There are theoretical basis (for example, [9]) of the validity of applying *min* operator in (9)-(11). However, there exist many families of aggregation operators [10] that may be used in place of *min* operator. Considering this, it is possible to generalize (9) as follows:

$$\mu_D(x) = \text{agg}\,(\mu_{A_1}(x), \mu_{A_2}(x),...,\mu_{A_q}(x)), \quad x \in L. \quad (12)$$

Despite that some properties of the aggregation operators have been established, there is no clear and intuitive interpretation of these properties, nor unifying interpretation of the operators themselves [10]. It is possible to state the following question: among many types of aggregation operators, how is one selected, which is adequate for a particular problem, and how is the selection justified? Although some selection criteria are suggested in [8], the majority of them deals with empirical fit. Thus, it is possible to assert that the selection of the operators, in large measure, is based on experience. Considering this, the present paper includes results of experimental comparing the validity of using *min* operator and *product* operator. The last operator has found wide applications in decision making problems. Its use reduces (12) to

$$\mu_D(x) = \prod_{p=1,...,q} \mu_{A_p}(x) \quad (13)$$

and permits one to construct the problem

$$\max \mu_D(x) = \max_{x \in L} \prod_{p=1,...,q} \mu_{A_p}(x) \quad (14)$$

to find

$$x^0 = \arg \max_{x \in L} \prod_{p=1,...,q} \mu_{A_p}(x). \quad (15)$$

To obtain the solution (11) or (15), it is necessary to construct the membership functions $\mu_{A_p}(x)$, $p = 1,...,q$ that reflect a degree of achieving "own" optimums by $F_p(x), x \in L, p = 1,...,q$. This demand is satisfied by using the membership functions

$$\mu_{A_p}(x) = \left[\frac{F_p(x) - \min_{x \in L} F_p(x)}{\max_{x \in L} F_p(x) - \min_{x \in L} F_p(x)} \right]^{\lambda_p} \quad (16)$$

for objective functions that must be maximized or the membership functions

$$\mu_{A_p}(x) = \left[\frac{\max_{x \in L} F_p(x) - F_p(x)}{\max_{x \in L} F_p(x) - \min_{x \in L} F_p(x)} \right]^{\lambda_p}. \quad (17)$$

for objective functions that must be minimized.

In (16) and (17), $\lambda_p, p = 1,...,q$ are importance factors for the corresponding objective functions.

The construction of (16) or (17) demands to solve the following problems:

$$F_p(x) \to \min_{x \in L}, \quad (18)$$

$$F_p(x) \to \max_{x \in L}. \quad (19)$$

Thus, the solution of the problem (5) demands analysis of $2q+1$ monocriteria problems (18), (19) and (10) or (14), respectively.

Since the solution x^0 must belong to $\Omega \subset L$, if we solve, for example, the problem (10), it is necessary to construct the membership function

$$\bar{\mu}_D(x) = \mathop{\wedge}_{p=1}^{q} \mu_{A_p}(x) \wedge \mu_P(x)$$
$$= \min\{\min_{p=1,...,q} \mu_{A_p}(x), \mu_P(x)\} \quad (20)$$

where $\mu_P(x) = 1$ if $x \in \Omega$ and $\mu_P(x) = 0$ if $x \notin \Omega$.

It should be noted that corresponding building procedures for solving the problem (10) or (14) provides the line of obtaining $x^0 \in \Omega \subset L$ in accordance with (20) [11]. Thus, it can be said about equivalence of $\bar{\mu}_D(x)$ and $\mu_D(x)$, that makes it possible to give up the necessity of implementing a procedure of determining $\Omega \subset L$. This allows one to use the multicriteria approach in solving diverse problems of planning and control, including the allocation of resources or their shortages.

4 Multicriteria Power and Energy Shortage Allocation

The AIDMS has been developed to solve the problem (5). Its calculating kernel destined for solving the problem (10) or (14) is based on a non-local search that is a modification of the Gelfand's and Tsetlin's "long valley" method [11].

The AIDMS includes a procedure for building a term-set [8] of the linguistic variable S - *Limitation for Consumer* (the initial available term-set is *T(S)=* <*Near*, *Approximately*, *Slightly Less*, *Considerably Less*, *Slightly More*, *Considerably More*>) to provide DM with the possibility to consider conditions that are difficult to formalize. The consideration of conditions defined by the linguistic variable does not change the solution technology: the availability of m additional conditions leads to $p = 1,...,q + m$ in (9)-(11) and (13)-(15).

Furthermore, the AIDMS includes procedures for building and correcting the vector $\lambda = (\lambda_1,...,\lambda_q)$ of the importance factors. The group procedures are related to ordering goals and to giving marks for them. The individual procedure is based on the Saaty approach [12] associated with processing of paired qualitative comparisons of the importance of goals. Following the procedure, DM has to indicate which among two goals is more important with estimating the perception of distinction using a rank scale. The comparisons allow one to build a matrix $\mathbf{B} = [b_{pt}]$, $p,t = 1,...,q$. The eigenvector corresponding to its maximum eigennumber serves as $\lambda = (\lambda_1,...,\lambda_q)$ The use of this procedure allows for testing the quality of comparisons from the standpoint of their transitiveness. If the maximum eigennumber of $\mathbf{B}$ is close to q , then $\lambda_p, p = 1,...,q$ are acceptable; otherwise the comparisons should be reconsidered.

As a simple example of multicriteria power shortage allocation on the basis of decision making in a fuzzy environment with using *min* and *product* operators as well as the traditional scalarization method [6] (this method has found the most widespread use in power engineering problems), we can consider the following problems.

It is necessary to allocate power shortages A^1=20000 kW, A^2=30000 kW, A^3=40000 kW, A^4=50000 kW and A^5=60000 kW among 6 consumers with considering the goals 1, 12, 15 and 16 listed above. These goals are described by the linear objective functions (1) and we have:

$$F_p(X) = \sum_{i=1}^{6} c_{pi} x_i , \quad p = 1,15,16 \qquad (21)$$

that must be minimized and

$$F_{12}(X) = \sum_{i=1}^{6} c_{12,i} x_i \qquad (22)$$

that must be maximized.

Table 1 includes initial information to solve the problems. The results obtained on the basis of the Bellman-Zadeh approach (x^0), use of *product* operator (x^{00}) and the traditional method (x^{000}) for A^1=20000 kW and A^5=60000 kW are presented in Table 2 and Table 3.

To reflect the quality of solutions obtained on the basis of different approaches Table 4 includes the mean magnitudes of absolute values of deviations of membership function levels, for example, $\mu_{A_p}(x^0)$ from their mean levels $\hat{\mu}_{A_p}(x^0)$ calculated as follows:

$$\Delta(x^0) = \frac{1}{q}\sum_{p=1}^{q}\left|\mu_{A_p}(x^0) - \hat{\mu}_{A_p}(x^0)\right| . \qquad (23)$$

Table 1: Initial information

i	$c_{1,i}$, monetary units/kWh	$c_{12,i}$	$c_{15,i}$	$c_{16,i}$, hours	A_i , kW
1	1.50	5.40	0.63	15.30	14000
2	4.10	6.20	0.33	17.20	6000
3	1.40	5.80	0.28	21.10	4000
4	2.20	5.30	0.21	18.50	7000
5	1.20	4.20	0.26	17.40	19000
6	2.13	4.70	0.36	19.60	14000

Table 2: Power shortage allocation

i	$x^{1,0}$	$x^{1,00}$	$x^{1,000}$	$x^{5,0}$	$x^{5,00}$	$x^{5,000}$
1	5398	5804	0	13020	14000	14000
2	2515	1104	0	5076	5731	6000
3	2399	870	0	3986	4000	4000
4	950	6898	1000	6223	7000	7000
5	6738	5324	19000	19000	19000	19000
6	0	0	0	12695	10269	10000

Table 3: Levels of membership functions

p	1	2	3	4
$\mu_{A_p}(x^{1,0})$	0.604	0.605	0.605	0.606
$\mu_{A_p}(x^{1,00})$	0.615	0.590	0.633	0.630
$\mu_{A_p}(x^{1,000})$	0.974	0.020	0.951	0.596
$\mu_{A_p}(x^{5,0})$	0.428	0.431	0.428	0.428
$\mu_{A_p}(x^{5,00})$	0.366	0.700	0.353	0.714
$\mu_{A_p}(x^{5,000})$	0.321	0.750	0.357	0.741

Table 4 covers the cases reflected in Table 2 and Table 3 as well as A^2=30000 kW, A^3=40000 kW and A^4=50000 kW. The data of Table 4 bring out clearly that $\mu_{A_p}(x^0) \succ \mu_{A_p}(x^{00}) \succ \mu_{A_p}(x^{000})$. The high quality of the solutions x^0 is also confirmed by inequalities $\min_p \mu_{A_p}(x^0) > \min_p \mu_{A_p}(x^{00})$ and $\min_p \mu_{A_p}(x^0) > \min_p \mu_{A_p}(x^{000})$ observed for all cases. The inequalities $\min_p \mu_{A_p}(x^{00}) > \min_p \mu_{A_p}(x^{000})$ also take place for all cases. This permits one to assert that decision making in a fuzzy environment even with using *product* operator provides us with solutions more harmonious than on the basis of the traditional method.

Table 4: Mean magnitudes of deviation absolute values

Δ	A^1	A^2	A^3	A^4	A^5
$\Delta(x^0)$	0	0.003	0.052	0.060	0.001
$\Delta(x^{00})$	0.015	0.010	0.100	0.192	0.174
$\Delta(x^{000})$	0.327	0.327	0.290	0.194	0.203

5 Conclusion

The problems of power and energy shortage (natural or associated with the advisability of load management) allocation have been formulated within the framework of multicriteria optimization models to consider and to minimize diverse consequences of limiting consumers as well as to create incentive influences for them. The general list of goals has been developed. This list is of a universal character and can serve for building models at different levels of load management hierarchy. It has been shown the utility of applying the Bellman-Zadeh approach to analyzing multicriteria models. The advantages and capabilities opened by its use have been demonstrated. The results of the paper have been realized as the adaptive interactive decision making system. Its application permits one to improve the validity and factual efficiency in allocating power and energy shortages.

The results of the paper may directly be extended to energy market problems, whose solution is related to functions of the Independent System Operator or other independent institutions [3]. It may demand:

1. Additional substantial analysis of energy market problems for adapting the general list of goals. The list is to serve for building models at different levels of territorial, temporal and situational hierarchy of planning and operation, considering their different structures [3];

2. Construction of diverse types of sensitivity indices that are necessary to solve energy market problems. This construction is expedient to realize on the basis of experimental design techniques [13];

3. Development of aggregation and decomposition procedures to solve the electricity market problems for different territorial levels. This development is also related to posing and solving problems of planning and operation of multi-zone markets [3].

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