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Method of adequacy optimization of electric power systems under market conditions

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Abstract. We suggest a new approach to optimization of the adequacy of electric power system under market conditions which involve competition of various interests of market agents. This feature makes unsuitable of traditional methods for optimization of the adequacy of electric power system. The reliability analysis of the variants of development of electric power system is carried out on the base of the Monte Carlo method. The profit of generating companies is calculated by the obtained reliability indexes which characterize some variant of electric power system development. The investigated variant of development of electric power system is effective if all generating companies choose a sufficient level of reliability that satisfies the consumer. The results of experimental research are presented in the paper.

1 Introduction

The reliability level of electricity supply depends of power reserves and power transmission lines capacity. These factors define additional costs and consequently electricity prices. If consumer is interested in high level of reliability, then he should agree to pay for this service.

The problem of electric power systems development taking into account adequacy is solved traditional on the basis of cost minimization for this development. There are following classical models of electric power systems adequacy optimization. The first one is problem of searching of ways for achieve of the given meaning of reliability index in nodes of electric power systems with minimal costs [1]. The second one is problem of minimization of costs and mathematical expectation of costs of undersupply of energy [2]. The problem of maximization of reliability index under the given cost level is third main classical problem. For solving these problems researchers take information of possible aggregate demand of power and available and planning generators in nodes, configuration and capacity of network. Today the basic method for realization of these models is interactive approach. The main idea of the method consists in adequacy analyze expert's variants of energy system development [3].

Today electric power systems are liberalized in many countries. Liberalized energy markets have different features [4] which we must take into account under planning of development of electric power systems. The type of market interaction is a reason of choice of behavior criteria of energy market agents such as profit maximization for generator and network companies or maximization of social welfare for energy system operator or utility maximization for customers. The result of interaction of agents is market equilibrium with formed price and quantity of power energy and consumption, quantity of used generators and others. This equilibrium is different of perfect competitive equilibrium. That's way we must use noncompetitive models for solving the problem of development of energy system.

Taking account of the reliability of energy supply under definition of plan on development of energy system in market conditions is seriously complicated of solving of the discussed problem. The model of regulated monopoly with traditional method of minimizing of costs could be expanded for analyze of perfect competitive market. Further development of model on the base of no perfect competitive is more complicated, for example, for oligopoly of energy market. The common way for solving of these problems is not exist. We'll describe some existing approaches and define the place of our model.

The authors in [5] offer to compute of efficiency of investment in electricity market with using reliability index LOLP (Loss of Load Probability) [6] which characterizes the probability of the load loss. Formed meaning of this index is took equal as one day of the load loss in ten years. In our model we use near idea and offer our approach of forming of consumer price.

Ensuring generation adequacy in electric power system in some market conditions such as conclusion of bilateral treaty is discussed in article [7]. There is the problem that the compute of reliability is very simplified. And the reliability index LOLP can't take into account more difficult events such as stimulus of keeping of generators which works in peak time. It can be reason of mismatch between prices on energy market and payments for power market.

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There are articles in which possible development of electric power system is computed under competitive interactions at first. Then they estimate and compare reliability of the computed variants of the development of system [8, 9]. In our model we consider the set of variants of system development which be obtained by algorithm [1]. We analyze reliability indices and profit of companies for every electric power systems variant. After that the optimal variant for market agents is chose.

Choosing of the best variant of electric power systems development can be accepted on the government level or on level of generating and network companies. One of the way for union of the opposite interests is two stages approach. On a first stage investment decisions are accepted. Quantity of generated power and prices are computed on the second stage. Similar approach is presented in [10].

Some models of electric power systems development under regulated monopoly and oligopoly with taking account of quality of energy supply is discussed in [11]. Calculating of quality of energy supply is simplify in this model. The authors input additional condition for reliability index in the optimization problem.

We suggest of two-stage approach to optimization of adequacy of electric power systems under market conditions. At the first stage we consider and estimate of adequacy level of several expert variants of electric power system development. At the second stage parameters of market equilibrium are computed for all market agents such as consumers and generating or network companies. As a result, we choose of the most effective variant of development by maximization criteria of social welfare and high level of adequacy. The one of new ideas is presentation of price as function of reliability index. In addition, we can apply the developed method to estimate of effectiveness of different market types.

2 Method of reliability optimization

In market conditions the problem should be solved taking into account different interests of economic agents such as generation and network companies and consumers. This fact determines of changing of optimization criteria. Instead of minimization of system costs we should maximize payoff function of each agent [7, 12]. Decision making of economic agents is based on results of adequacy estimation of electric power system. Effective method for such problem is developed earlier [13].

We modified the method for adequacy analysis of electric power system in market conditions. The method consists of four main blocks.

1. *Modeling of random states of electric power system*. Each state is characterized of the set of random values such as load and available generator capacity in nodes, power line capacity.

2. *The model of power shortage estimation of electric power system*. Power shortage is estimated for each random state of electric power system. The model of power shortage estimation with quadratic power losses in power lines [13] is used in this stage. Taking account of quadratic losses guarantees uniqueness of deficit distribution over system nodes.

3. *Profit computation*. Profit of generation companies is computed with penalties for electricity sacrifice. There are two ways for price definition. The first one is considering of generation companies as price takers. The other one consists in taking into account service quality elasticity of demand.

4. *Computation of reliability indexes*. Reliability indices are probability of no shortage system work, mathematical expectation of power shortage and electricity sacrifice of consumers, coefficient of availability of power.

Optimal set of equipment in electric power system is defined as a result of comparison of variants of electric power systems development. That's way we are adding the next stage of computation.

5. *Comparison of reliability indices with companies' profit according to different configurations of electric power system*. On this stage it is choosing of optimal variant of system development which balances reliability level necessary for consumer and profit margin of generation and network companies. Maintaining the Integrity of the Specifications

3 The model of power shortage estimation

Let's consider the scheme of electric power system. The electric power systems scheme consists of *n* nodes and set of links between nodes. According to method for estimating of electric power systems adequacy it is necessary to simulate random states of electric power systems a many times. The simulations are occurred on a base of Monte Carlo method.

Let *N* is the given number of electric power systems states. Each state is characterized by set of means of random values such as generating capacity $\bar{x}_i^k$, load value $\bar{y}_i^k$ in the node *i*, line capacity $\bar{z}_{ij}^k$ between nodes *i* and *j*, $i=1,\dots,n$, $j=1,...,n$, $i \neq j$, $k=1,...,N$.

We use following problem [13] for power shortage estimation of random states of electric power systems. The power x_i and the load y_i in node *i*, power flow z_{ij} from node *i* to node *j*, $i=1,...,n$, $j=1,...,n$ are variables of the problem. The considered problem for some *k*, $k=1,...,N$, is

$$\sum_{i=1}^{n} y_i \to \max, \tag{1}$$

subject to the constraints

$$x_i - y_i + \sum_{j=1}^{n}(1-a_{ji}z_{ji})z_{ji} - \sum_{j=1}^{n} z_{ij} = 0,\ i=1,\dots,n, \tag{2}$$

$$0 \le y_i \le \bar{y}_i^k,\ i=1,\dots,n, \tag{3}$$

$$0 \le x_i \le \bar{x}_i^k,\ i=1,\dots,n, \tag{4}$$

$$0 \le z_{ij} \le \bar{z}_{ij}^k,\ i=1,\dots,n,\ j=1,...,n,\ i \neq j \tag{5}$$

where positive coefficients of power losses a_{ij} are given.

As a rule, the adequacy analysis of electric power system is realized for year. Every hour of work of electric power system is modeled. The failures of generators and power lines are used as random parameters. The repair time of equipment and fluctuations of load in the year are taking account in modeling. The rules of simulations of random values such as available capacity of generator and power line or load value are discussed in [14].

Let set of $\hat{x}_i^k$, $\hat{y}_i^k$, $\hat{z}_{ij}^k$ is optimal solution of the problem (1) – (5), $k=1,...,N$, $i=1,\dots,n$, $j=1,...,n$, $i \neq j$. The optimal value of power shortage in node *i*, $i=1,\dots,n$, is defined by the formula

$d_i^k = \bar{y}_i^k - \hat{y}_i^k$, $k=1,...,N$.

The state of electric power systems is deficit if the value

$$d^k = \sum_{i=1}^{n} d_i^k$$

is not equal to zero. Let is numerate all deficit states of electric power systems and define of the ircommon quantity as H. Then the probability of without shortage work of electric power systems are computed by next formula

$$P = 1 - \frac{H}{N}.$$

This index is corresponded to index LOLP.

Mathematical expectation of power shortage in nodes of energy system is computed by next rule

$$MD_i = \sum_{j=1}^{H} \frac{d_i^j}{N}, \ i=1,\dots,n.$$

That's way mathematical expectation of power shortage in electric power systems is calculated by

$$MD = \sum_{i=1}^{n} MD_i.$$

4 Modeling of the economic agents behavior

As a result of the reliability assessment of each equipment we find the set of reliability indices in the electric power systems. From the value of reliability indices depends on the willingness of consumers to pay for electricity (demand for reliability). Let r is the some reliability index (for example, the probability of without shortage work P), characterizing the frequent, duration and depth of failures. In the general case, instead r, an n-dimensional vector can be used, the components of which are the values of some reliability index obtained from the nodes of the system. We assume that the values of the index r cannot be below a certain level $\underline{r}$ and not above the level $\bar{r}$. The decision of N tasks to assess the power shortage for each scenario of electric power systems development through simulation allows to estimate the satisfied demand, the electricity generation in each node and the volume of power flows in the system

$$\tilde{y}_i = \frac{1}{N}\sum_{k=1}^{N} \hat{y}_i^k, \ \tilde{x}_i = \frac{1}{N}\sum_{k=1}^{N} \hat{x}_i^k, \ \tilde{z}_{ij} = \frac{1}{N}\sum_{k=1}^{N} \hat{z}_{ij}^k,$$

$i=1,\dots,n$, $j=1,...,n$, $i \neq j$. Using these indexes, we evaluate the actions of agents interacting in the electricity market.

The payment for reliability is the price that the consumer agrees to pay. For definiteness, it can be determined in the form of an increasing function $g(r)$. Note that the choice of the reliability index depends on the form of the function $g(r)$, which is demand function of electricity of a certain quality (reliability).

4.1 Modeling the demand for electricity

Several options are possible.

The first complicated variant of the demand specification is accounting for different types of consumers. In this case, the price function is determined for each type of consumer, or, for each network node. This requires determination of the reliability indices r_i for the individual nodes $i=1,\dots,n$ or individual groups of nodes. Then the price that the consumer is willing to pay at node i can be represented in the form:

$$g_i(r_i) = (r_i)^m p_i(\tilde{y}_i). \tag{6}$$

where $p_i(\tilde{y}_i)$ is the maximum price that the consumer is willing to pay in the node *i*, $i=1,\dots,n$, without of power failures; m is the parameterthatdetermineshowmuchwetakeintoaccountth ereliabilityfactor, $m \in [0, 1]$ (the higher m, the more important for the consumer the qualitative power supply). The function $g(r)$ in the form (6) is concave, increasing with respect to r.

The value of $p_i(\tilde{y}_i)$ can be determined through the generally accepted inverse demand function: $p_i(\tilde{y}_i) = \beta_i - \alpha_i \tilde{y}_i$, where coefficients β_i, α_i are the parameters of inverse demand function that satisfy the standard requirements. In our study, we assume that demand is not elastic, so the price is identically equal to the constant part of the inverse demand function: $p_i = \beta_i$.

The second way, when consumers are homogeneous and have the same preferences (some aggregated consumer). Then $\beta_i = \beta$ and $\alpha_i = \alpha$ for all $i=1,\dots,n$ and the inverse demand function is the same in all nodes

$$p = \beta - \alpha \sum_{i=1}^{n} \tilde{y}_i. \tag{7}$$

The same variant of demand can be connected with the configuration of the wholesale electricity market organized as a bilateral auction. In this case, an aggregate demand function is formed to integrate all consumers.

For the inelastic variant, the inverse demand function is $p = \beta$, and the price in the model is defined as

$$g(r) = (r)^m \beta.$$

In this case the price is the same for all nodes and dependent on the resulting index of reliability r.

4.2 Modeling the behavior of generating companies

After selecting a scenario for the development of electric power systems and analyzing its reliability, it is necessary to assess the profitability of this development variant for generating companies. We take into account the fact that different generating companies may have different owners.

Generating companies maximize their profits depending on the emerging price, which in turn depends on the reliability index r_i, $i = 1,\dots,n$, as well as on the parameters of the functions[a]. Suppose that a generating company $s = 1,\dots,S$ operates in several nodes $l = 1,\dots,L$. Then its profit is

$$\pi_s(r) = \sum_{l=1}^{L} g_l(r_l)\widetilde{x}_l - C_s\left(r, \sum_{l=1}^{L}\widetilde{x}_l\right), \qquad (8)$$

where $C_s\left(r, \sum_{l=1}^{L}\widetilde{x}_l\right)$ is costs of the generating company s, $s = 1,\dots,S$ depending on the reliability index r_l in each node $l, l = 1,\dots,L$, power generation and capital costs of electricity generation. The cost function is increasing and convex. In this case, the following relation must be carried out

$$C_s\left(\underline{r}, \sum_{l=1}^{L}\widetilde{x}_l\right) < g(\underline{r}).$$

This property reflects the willingness of producers to develop a power system to increase their profits. As a cost function, it is possible to use a linear, quadratic and exponential function. These cases differ depending on the rate of increase in costs for an increasing level of reliability. Under the cost we mean the level of operational and capital costs, which determine the value of the index r. We form cost function on the basis of simulation modeling, comparing costs and balances reliability.

For the case of aggregate demand, the profit function for an individual company is as follows:

$$\pi_s(r) = \sum_{l=1}^{L} g(r)\widetilde{x}_l - C_s\left(r, \sum_{l=1}^{L}\widetilde{x}_l\right).$$

Each company s, $s = 1, \dots, S$, solves the problem of maximizing profit by the reliability index r

$$\pi_s(r) \to \max_r, \qquad (9)$$

$$\underline{r} \le r \le \overline{r}. \qquad (10)$$

It should be noted that the profit function is concave by virtue of convexity of costs and concavity of revenue for this index. The set of admissible solutions of the problem is compact, therefore, the problem has a solution. The solution of problem (9) - (10) is the value of reliability index that can provide this company to maximize its profits. At the same time, the profit of the company s, $s = 1, \dots, S$, depends on the actions of other generating and grid companies. Problem (9), (10) refers to the class of stochastic programming problems, for solutions to which are widely used approaches, based on the Monte Carlo method [15].

[a]In this formulation, the mechanism of competitive price formation in the market is not taken into account.

4.3 Modeling the behavior of grid companies

The network component influences the price of demand. For each case, we have the costs necessary for the transfer of electricity. In our model, we consider them aggregated without separately calculated profit network company. This is due to the usual market structure, where network companies are allocated to the natural monopoly segment and are regulated by the state. The profit of such a company can be considered zero (normal). Due to the network additive, electricity can be significantly more expensive, so this factor needs to be monitored.

5 The choice of the best case of the development of the electric power system

Thus, the reliability analysis of different variants for the development of electric power system can be compared with the level of balances reliability, with the profit generating companies $\pi_s(r)$ and with the transmission costs, which are reflected in the price level $g(r)$. In our model, the choice of the best equilibrium variant is based on the solution of the problem (9) - (10) by each company. The generating company maximizes profit, determining for itself the optimum level of reliability. The investigated variant of electric power systems development is considered effective if all generating companies choose a sufficient level of reliability or level of reliability falling into a predetermined interval that satisfies the consumer. If at least one company chooses low level of reliability of electricity supply, it then this indicates the ineffectiveness of installed capacity, and the scenario is recognized as not optimal.

6 Experimental researches

We carry out the verification of the developed approach by the test scheme of electric power systems consisting of 5 nodes and 5 links (Fig. 1). Table. 1 shows: characteristics of generating capacities (units with a capacity of 100 MW with an accident rate of 0.045); data on absolute load maxima; information on inter-node connections (in electric power systems power units are connected by a transmission line with a capacity of 135 MW with an integral accident rate of 0.011 per 100 km and a loss factor of 0.0000001661).

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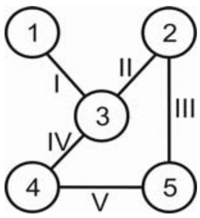

Fig. 1. The design scheme of the electric power system.

The given energy system is deficit in spite of excess of summary generation over absolute maximum of system load. The reliability index of system work without deficit P is 0.9629 under *N*=10000. The first node of these energy systems is deficit. The mathematical expectation of power shortage in this node is equal 1.4005 MW. The total mathematical expectation of power shortage is 1.4128 MW.

Table 1. Technical characteristics of the investigated EPS

Node number	**Total power in the node, MW**	**Absolute maximum of load, MW**	**Link num-ber**	**Number of transmission lines in the link**	**Length, Km**
1	500	700	I	2	200
2	1000	700	II	2	100
3	1400	1300	III	1	300
4	1000	1000	IV	2	200
5	1200	1100	V	2	300
System	5100	4800			

For demonstration of developed method, we suggest to consider of four possible variants of development of EPS. The first one (case 1) is installation of additional generator with a power of 100 MW in node №1. The second one (case 2) is extension of capacity of link I by 135 MW with building corresponding transmission line. The third one (case 3) is installation of a two additional generators with a power of 100 MW in node №1. The fourth one (case 4) is installation of additional generator with a power of 100 MW in node №1 and extension of capacity of link I by 135 MW with building corresponding transmission line.

We consider the homogeneous consumers with similar preferences for modeling of economic agent's behavior. That is way demand function (7) is $p = \beta - \alpha\sum_{i=1}^{n}\tilde{y}_i$ with $\beta = 6845$, $\alpha = 0.81$. Payments for reliability are computed by formula (6). Here P is probability of system work with out power deficit. Reliability index P is computed for some variant of EPS development. m - parameter defining the type of consumer. If it is small, then reliability is not a priority for the consumer. If it is large, the consumer appraises very much the reliability. We consider $m \in \{0{,}2; 20\}$.

The first test was realized for one generating firm. The cost function of generating company is quadratic $C(\tilde{x}) = 0.08(\sum_{i=1}^{n}\tilde{x}_i)^2 + 50\sum_{i=1}^{n}\tilde{x}_i$. Generator profit is computed by

$$\pi = g\sum_{i=1}^{n}\tilde{x}_i - 0.08(\sum_{i=1}^{n}\tilde{x}_i)^2 - 5\sum_{i=1}^{n}\tilde{x}_i \ .$$

Table 2 shows the results of calculations for the 4-th cases of the development of EPS at N = 10000. The probability of failure, the price (7) and the total output are calculated.

Table 2. The characteristics of EPS

Case EPS	***P***	***MD***	$\sum_i y_i$	***P***
Initial	0.965	1.44	3560	3928.83
1	0.994	0.18	3563	3928.81
2	0.997	0.06	3558	3934,36
3	0.999	0.05	3566	3928.81
4	0.999	0.00	3560	3928.72

Specific capital cost for the installation of 1 kW of generating capacity is $1000. [16]. This level of cost corresponds to setting blocks of condensing power station running on gas. The unit capital cost for the installation of 1 kilometer of the electrical transmission line is 3.6 UE per 1 kW [16]. These costs correspond to 220 kW ETL. The coefficient of reduction is 0,065 (refund within 15 years).

We compare development cases for two kinds of consumers. The first one doesn't consider the energy reliability a priority. In this case $m = 0{,}2$ for realistic price *g,* which a consumer is willing to pay in accordance with reliability, decreasing insignificantly in comparison with the price without taking into account the reliability P. The table 3 shows the company profit (we are considering only one operating company here), the price taking into account the reliability, welfare for all four cases.

Table 3. Calculation results for $m = 0{,}2$

Variant of EPS	**g**	**Profit**	**Welfare**
Initial	3905	12673540	**12970983**
1	3925	6257528	6560656
2	3932	12763828	6740495
3	3928	-224835	81487
4	3933	6272965	252490

The original variant is advantageous for this kind of consumer. Costs for the installation of new generating capacity and electrical transmission lines don't pay off. We compare all cases by the criterion of the social welfare. The maximum is reached with the initial version. The third case is unprofitable for generating companies because of the negative benefit.

The results change if the consumer appreciates the reliability $m = 2$ (table. 4). Not the initial variant, but the variant with one additional power line (case 2) is a winning one. The others options are not the best. At the same time, if one chooses from them, then the case with the installation of the power transmission line (case 4) is more effective than the one with the installation of two additional capacities (case 2).

Table 4. Calculation results for $m = 2$

Variant of EPS	g	Profit	Welfare
Initial	1351	3580553	3877995
1	3281	3961147	4264275
2	3595	11565675	**5542342**
3	3928	-224835	81487
4	3933	6272965	252490

7 Conclusion

We suggest a new approach to optimization of reliability of electric power system under market conditions. In market conditions the problem should be solved taking into account a different interests of economic agents s. This fact determines of changing of traditional methods for solving the discussed problem.

The reliability analysis of variants of development of electric power system is based on method with using Monte Carlo method for simulations of random values. We use the model of power shortage estimation with quadratic power losses in power lines for analyzing each random state of energy system. The model guarantees uniqueness of deficit distribution over system nodes and single-valuedness of computed reliability indexes.

The reliability indexes are computed for each variant of development of electric power system. Profit of generating and network companies depends on meanings of reliability indexes. After analyzing all development variants companies will choose the reliability level which is optimal for them. They can provide this reliability level by inputting new generating and network equipment in the energy system. If all companies, choose the same development variant then this is Nash equilibrium which may be not the best solution for the system. If the companies, choose the different development variants then we accept a decision about an effective variant. Each company should have a positive profit and the reliability index should not be below some given level. The experimental research of the developed method is suggested on test scheme of electric power system which is constructed on the base of real technical data.

Further it is necessary concretization of network company's role to develop and verificate our model. Also we must will realize wide computing experiment and compare the different models of consumer behavior.

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