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APPLICATION OF RANDOM SEARCH ALGORITHMS AT OPTIMIZATION OF ELECTRIC ENERGY QUALITY IN NETWORKS OF STATIONARY RAILWAY ENTERPRISES

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The possibility of constructing the optimal control system of electric energy quality based on the established deviation and asymmetry of voltage at stationary railway enterprises applying the principle of correcting device decentralized arrangement has been shown.

In modern conditions the currency of works directed to increase of efficiency of using fuel-energy resources grew in connection of transition to market relations. Decrease of specific electric energy discharges by enterprises of rail transport stationary power engineering is the important component of energy-saving problem in the field. Currently there is a majority of procedures directed to decreasing the loss and increasing the energy efficiency of electric equipment; they may be combined in three interconnected directions: efficient control of the equipment operation mode, control of electric energy quality (EQ), increase of interest in engineering stuff motivation.

EQ influences considerably the power-supply system functioning. Energy processes in the equipment accompanying electric energy conversion into other kinds of energy depend, to a large extent, both on characteristics of supplied electric energy and on physical processes at energy conversion (into other kinds or electric energy with other parameters). As it is known active power transfer to consumer in ac voltage systems is accompanied by additional inactive component which increases total losses of electric energy. All those components which are caused by pulsation, asymmetry and unharmonicity of voltage and current determining EQ are referred to inactive energy.

Currently the approach to any problem requires application of optimization methods. Their aim is to determine the best solution by the accepted criteria of the majority of possible ones satisfying several restrictions. The last decades of XX c new methods of solving optimization problems: heuristic algorithms, evolutionary programming, genetic algorithms, fuzzy logic techniques, neural networks, random search methods and others were developed along with spread of classical approaches of mathematical programming [1, 2]. Each approach to solution of optimization problem has its advantages and disadvantages, the choice of one or another method often depends on a type of optimizable expressions, problem dimension, the required accuracy of solution etc. In some cases the hybrid methods which combine a number of simple ones are more suitable to be used.

As the researches showed the random search should be preferable at system approach to solution of EQ optimization problems. The random search includes the techniques of solving optimization problems which do not require knowledge about strongest decrease (increase) direction of an efficiency function. In the most general case the random search algorithms determine the collection of points around the most optimal point for i iteration; if in one of the examined points the efficiency function is less than in the current one then this point becomes the base for the search on (i+1) iteration. The applied algorithms allow solving the optimization problems with nondifferentiable, stochastic and broken efficient functions; owing to the principle of operation itself the direct search algorithms are the most efficient at search of global extremums for the complex systems [1–3].

The branched structure of low-voltage distribution networks of non-tractive railway consumers contains a majority of power consumers functioning in various modes according to engineering processes. Intrashop equipment is galvanically interacted that results in continuous conducted intercoupling [4]. Quality indices of electric energy in different network nodes determined by exchange of inactive power constituent differ both in structure and quantitative criteria of estimating indices by SS 13109-97. Inactive energy constituent increases electric energy loss, influences negatively the electric equipment, adjacent systems etc., therefore it is necessary to limit its distribution in the network using the EQ control system. Selection of nodes of CD arrangement, their functionalities should be determined within the limits of technical and economic design individually for each stationary railway enterprise.

The main task of **optimal control of electric energy quality** in networks of non-tractive railway consumers is minimization of exchange of inactive energy constituent between the electric equipment and outer system. As it is shown in [5] in controlling the inactive power constituent the energy-saving potential is hidden. By the authors' opinion it may be achieved by the optimal control of state space of several engineering tools arranged in decentralized order. In the most cases the best variant is CD connection directly at each distorting load (linear loads with inertia members may be referred to distorting loads as they increase current effective value). In this case the load relative to the network possesses purely active resistance and, therefore, inactive constituent of power is absent.

In order to solve the optimization problem by the random search methods the expression (1) connecting the cost of the arranged CD and the cost of electric energy loss in distributing networks, taking into account loss in CD, is the most suitable to be used as the efficiency function:

$$\text{Cost} = \left[8,76 k_э \sum_{i=1}^{N} R_i I_i^2 + \left(E_н k_{ку} \sum_{i=1}^{N_{ку}} Q_i + И \right) \right] \to \min, \quad (1)$$

where $k_{ку}$ is the incremental cost of CD, r/kVAr; $N_{ку}$ is the number of the arranged CD; Q_i is the reactive power of i CD, r/kVAr; $k_э$ is the incremental cost of electric energy, r/kWn; N is the number of nodes of distributing network; R_i is the active resistance of the i branch, Ohm; I_i is the effective current value of the i branch, A; $И$ are the annual costs of manufacturing for CD maintenance, r/year; $E_н$ is the standard efficiency factor of capital investment, 1/year.

Thus, the minimized functional determines annual loss in enterprise networks (the first summand) and the costs for installation and maintenance of EQ control system (the second summand in brackets). If it is necessary the restriction may be imposed to the rated capacity of CD, which determines investment.

Let us consider a filter of the first order in the form of series LC-circuit as the CD. It is connected in selected points with the deficiency of reactive power and adjusted to maximal highest current harmonics, at reactive power excess – the reactor of the required capacity. It should be noted that series connection of capacitor and reactor is necessary for decreasing a probability of appearance of parametric resonance in the system «CD – network» on frequencies of the highest harmonics.

Let us show the possibility of solving the simplest task of EQ optimization by current (voltage) asymmetry, steady-state voltage deviation and reactive power compensation, by criterion of electric loss minimum in the case of static loads (for average values of active, reactive powers of loads) of meshed system by the random search method. In this case it should be taken into account that electric loss optimization supposes uniform current phase distribution, i.e. EQ improvement by voltage asymmetry in three-phase nodes [6].

Algorithm of EQ optimization is introduced in Fig. 1. Let us show the implementation of EQ optimization algorithm by example of electric network of 0,4 kV of random topology with several single-phase and three-phase loads typical for stationary railway enterprises (Fig. 2).

The following notations: T1, T2 are the feeder transformers, АД is the induction motor, КУ is the compensating device, ЭТ is the electrothermy, ДП is the two-pulse converter, ДРЛ is the arc lamp, СТ is the welding transformer, СВ is the welding rectifier are accepted in Fig. 2.

The parameters of the equivalent circuit elements are introduced in Table 1; the nodes in which zeroes of transformer secondary windings are earthed according to the technical regulations are accepted as the points with zero potential.

The mathematical model of current distribution of electric network may be written down in matrix-topologic form in the following way

$$\dot{I} = \underline{Y} \cdot (S^t((S\underline{Y}S^t)^{-1} S(\dot{J} - \underline{Y}\dot{E})) + \dot{E}) - \dot{J}, \qquad (2)$$

where E is the column vector of complex branch emf (zero values for transformer branches), V; J is the column vector of current nodes complex (zero), A; Y is the diagonal matrix of complex branch admittance, Cm; I is the column vector of complex branch current, A; S is the connection matrix.

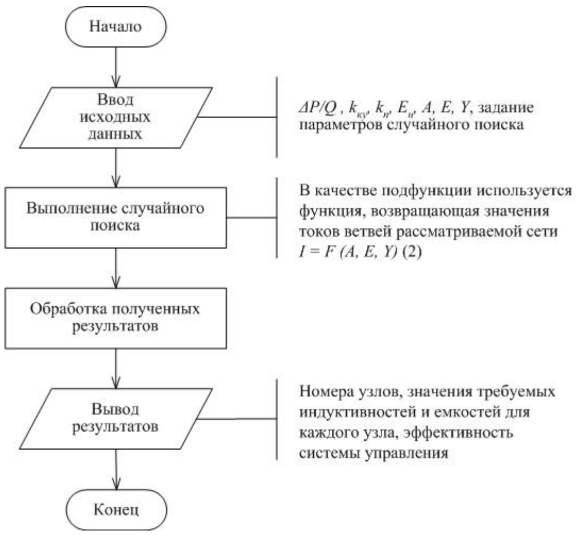

Fig. 1. *Algorithm of optimization of electric energy quality*

Начало – Start; Ввод исходных данных – Initial data input; Выполнение случайного поиска – Random search implementation; Обработка полученных результатов – processing the obtained results; Ввод результатов – Results input; Конец – Finish; Задание параметров случайного поиска – Definition of random search parameters; В качестве подфункции используется функция, возвращающая значения токов ветвей рассматриваемой сети – Function returning values of currents of the examined network branches is used as a subfunction; Номера узлов, значения требуемых индуктивностей и емкостей для каждого узла, эффективность системы управления – Numbers of nodes, values of the required inductance and capacities for each node, control system efficiency

For calculation let us accept the following values of branch conductivity corresponding to real equipment of distributing network (Table 1).

In this case the values of conductivities star connected in each node with conjugated common point with zero wire and triangle are the controlled variables (it is shown in the Figure only for one three-phase angle) and conductivities may take any values on imaginary axis.

For solving the system of linear algebraic equations of the model (2) the program written in the language of high level using the method of successive elimination of Gauss was used; this program is, in its turn, the subprogram at solution of optimization problem with application of the random search algorithms.

It is accepted at calculations that transformer phase voltages are constant by module and phase $\boldsymbol{E_A}$=220 V, $\boldsymbol{E_B}$=(220·$\boldsymbol{a}^2$) V, $\boldsymbol{E_C}$=(220·$\boldsymbol{a}$) V, where $\boldsymbol{a}=e^{j120}$ is the complex turn operator.

Ohmic loss in CD and active current components in network from CD are taken into account by addition of active component of CD complex conductivity provi-

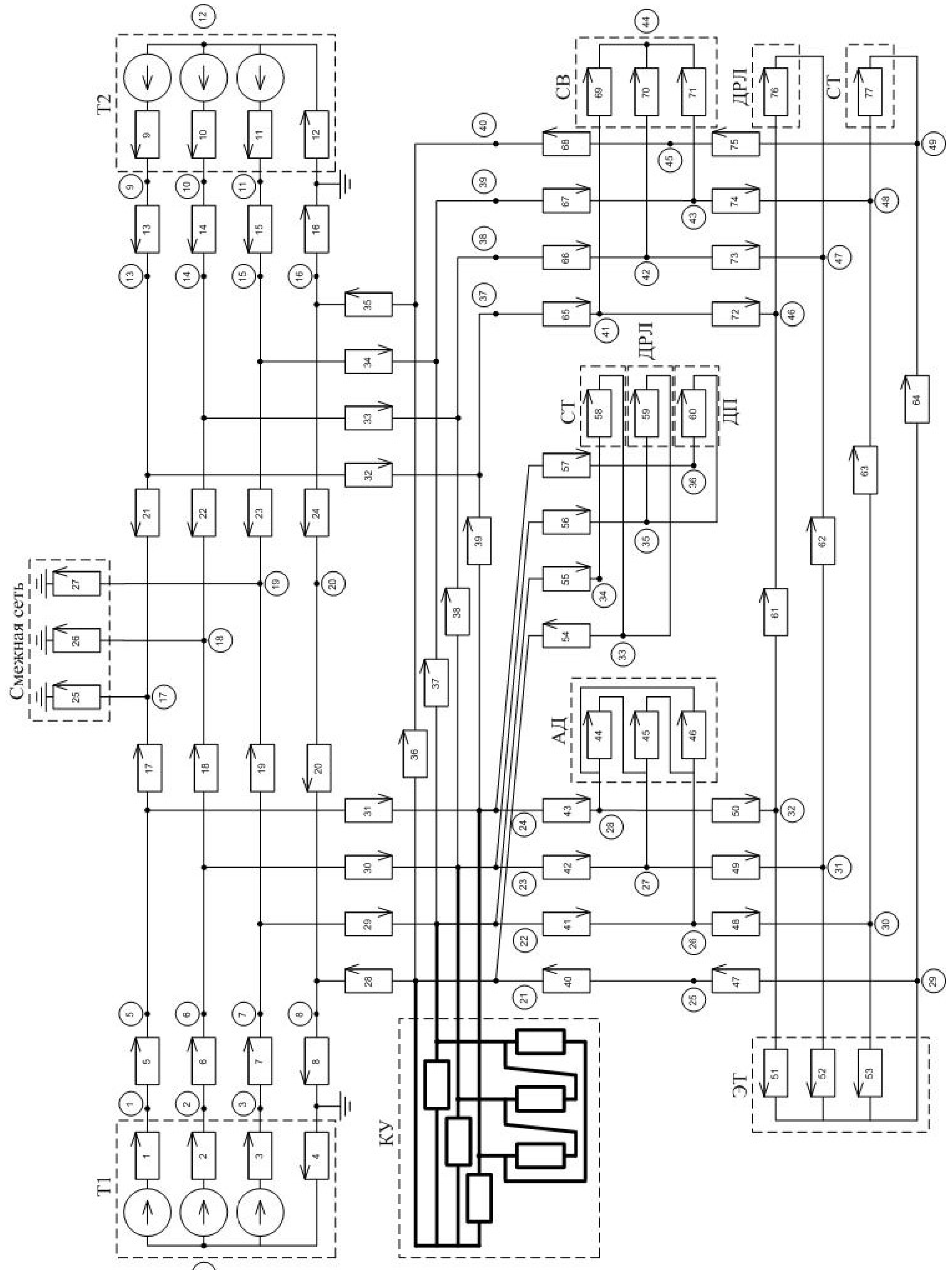

Fig. 2. *The equivalent circuit of meshed system*

ded that linear dependence of active loss on the reactive power:

$$\underline{Y} = \left(\frac{\Delta P}{Q} \pm j\right) b,$$

where $\Delta P/Q$ are the specific loss in CD, kW/kVar.

Table. 1. *Parameters of the equivalent circuit*

№	Name of process equipment	Type of equipment	№ of branches (Fig. 2)	Values of phase conductivity
1	Feeder transformer (T1)	TM 630/10	1, 2, 3	37-*j*153
			4	31-*j*130
2	Feeder transformer (T2)	TM 1000/10	9, 10, 11	55-*j*245
			12	47-*j*210
3	Adjacent network	$P_{ср}$=25 kW $Q_{ср}$=10 kVar	25, 26, 27	0,172-*j*0,069
4	Induction motor (IM)	4A160M6У3	44, 45, 46	0,096-*j*0,06
5	Electrothermy (ET)		51, 52, 53	0,207-*j*0,155
6	Welding transformer (WT)	СТЭ-24У	58	0,475-*j*0,356
7	Illumination (DRL)	DRL	59	0,041-*j*0,031
8	Double-pulse converter (DC)	TE1-50/12T-0УХЛ4	60	0,103-*j*0,077
9	Welding rectifier (WR)	BKC - 500	69, 70, 71	0,314-*j*0,258
10	Illumination (DRL)	DRL	76	0,021-*j*0,015
11	Welding transformer (WT)	STN-350	77	0,517-*j*0,387
12	Cable line	AAShV 95 mm²	5, 6, 7, 8	42,7-*j*13,2
13			13, 14, 15, 16	94-*j*29
14			17, 18, 19, 20	94-*j*29
15			21, 22, 23, 24	47,1-*j*14,5
16			28, 29, 30, 31	31,4-*j*9,7
17			32, 33, 34, 35	94,1-*j*29,1
18			36, 37, 38, 39	39,8-*j*12,1
19		AAShV 70 mm²	40, 41, 42, 43	180,2-*j*35,6
20			47, 48, 49, 50	126,1-*j*16,7
21			54, 55, 56, 57	360,1-*j*84,2
22			61, 62, 63, 64	96,1-*j*19,2
23			65, 66, 67, 68	111,6-*j*42,9
24			72, 73, 74, 75	161,1-*j*102,8

The following coefficients: $\Delta P/Q$=0,01 kW/kVar, $k_{ку}$=1500 r/kVar, $k_п$=1 r/kWh, $E_н$=0,12 are taken at calculations.

Performance of algorithm (Fig. 2) allows determining the connection nodes and necessary CD conductivities for minimization of currents of the distributing network branches. Listing of the program is introduced in Table 2.

Decrease of loss at use of decentralized CD arrangement may be estimated by the expression:

$$\Delta = \frac{Cost_{безКУ} - Cost_{сКУ}}{Cost_{безКУ}} 100\ \%. \qquad (4)$$

At CD arrangement in the given nodes the decrease of the reduced costs (4) amounts to (4) 31,54 % or in absolute magnitudes to 59 673 r/g. The lump-sum costs amount about 70...80 thousand rubles.

Currently the symmetric batteries of static capacitors are centrally arranged at the majority of enterprises of stationary railway power engineering. In this case (for the examined example of CD connection in nodes 1–3 and 9–11) the decrease of the effective current value in internal network is insignificant that is connected with a certain increase of voltage level in source points and, therefore, it does not allow obtaining considerable effect as at decentralized CD arrangement. Use of centrally arranged CD is required for observance of engineering regulations and agreements with power supply organizations.

Table. 2. *Program listing*

№ of nodes	Reactive component of CD conductivity, Cmho	Capacity, μF; *Inductance, mHn
29-30	0,0039	12,434
33-36	−0,3877	*8,21
33-35	0,00488	15,54
33-34	0,0166	52,84
46-49	−0,441	*7,21
48-49	0,0322	102,58
26-27	0,0156	49,74
27-28	0,0146	46,63
26-28	0,0166	52,84
30-31	0,0215	68,39
31-32	0,0527	167,86
30-32	0,05	161,64
35-36	0,113	360,59
34-36	0,175	556,42
41-42	0,074	236,25
42-43	0,025	80,82
41-43	0,074	236,25
46-47	0,063	202,05
46-48	0,24	764,69

Thus, use of linear mathematical model connecting mains voltages and currents, random search algorithms allows determining nodes of arrangement and the value of the required consumed (generated) reactive power for minimization of branch currents and improve electric energy quality by asymmetry, steady voltage deviation in nodes.

On the basis of stated above the following conclusions may be drawn.

1. Application of random search algorithms allows determining optimal locations of adjusters and their power without gradient methods. In this case maximum quantity of nodes of the examined network, i.e. objective dimension, depends only on computer capacity.
2. Complete description of network topology using the computing methods of meshed systems allows taking into account configuration of any network and selecting control actions in each individual case.
3. Further development of electric energy quality control algorithms supposes accounting of dynamically changing consumed power and control of electric energy quality using the adaptive control algorithms of adjusted correctors.

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GENERALIZED STATIC CHARACTERISTICS OF ELECTRIC POWER SUBSYSTEMS AND THEIR STEEPNESS FACTORS

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Representation of parts of electric power systems by generalized static characteristics has been considered. The design procedure of steepness factors of generalized static characteristics depending on features of equivalent subsystems is discussed. The generalized static characteristics and their steepness factors give the equivalent information on power subsystems and can be used at estimation of static aperiodic stability of power supply systems.

Steepness factors and load and generator effects are widely used in mode calculations and estimation of static stability of electric systems [1]. Static characteristics and steepness factors not only of separate elements of the systems but of their complex combinations forming subsystem are of practical interest. The generalized static characteristics and their steepness factors give the equivalent information on subsystem state. Let us singled out the subsystems in which there are no slack nodes by active power and subsystems containing slack nodes of active power depending on conditions accepted at equivalenting. In this paper the calculation expressions for determining steepness factors of static characteristics of complex electric power subsystems are introduced for the first time.

Let us turn to subsystem without slack nodes by active power. Let us arrange to call a part of a system having connection with the main or adjacent part in a single node *i*, the limited part (Figure). Let us suppose that in a certain initial steady-state condition in the main part of electric system the stationary disturbance occurred. It resulted in change of module ΔU_i and phase $\Delta\delta_i$ of node voltage to which the limited subsystem abuts. Circuit layout, composition of equipment (including consumers), transformation ratios, settings of the first and secondary regulators are stable in the given subsystem. The two latter conditions are adequate to constancy of source active power. Let us analyze the changes which occur in the singled out subsystem at alternate and independent occurrence of disturbances ΔU_i and $\Delta\delta_i$.

Under the action of applied disturbance ΔU_i (δ_i=const) the subsystem operating conditions are deformed. Active power of power sources is constant and load node power (according to static characteristics) and loss in network elements change. Unbalance of active (ΔP) and reactive (ΔQ) powers which tends to the node *i* is formed in subsystem.

At stationary increment of phase $\Delta\delta_i$ (U_i=const) the subsystem moves as a unit relative to synchronous axis of node *i*. Stress vectors of all nodes in subsystem change by the same angle as phase increment in common angle *i*. Reference angles of stress vectors in subsystem are constant. Its mode is constant as well that indicates the absence of subsystem reaction on the specified disturbance $\Delta\delta_i$. As the limited subsystem has the only connection with the main part then functional dependences

$$P_{ic} = P(U_i);\ Q_{ic} = Q(U_i) \qquad (1)$$

are the full mode equivalent of subsystem.

At known reset conditions of the system the generalized static characteristics are found out by calculations of a number of steady-state conditions of equivalenting subsystem at stress module variation of equivalenting node. Equivalenting node is accepted as a balancing one by active and reactive powers. Calculations allow introducing dependences (1) in Table, diagram or analytically at proper results processing.

The subsystem diagram is given in the form of passive multiport (*n*-pole network). Two-terminal networks substituting generators, sources of reactive power and load are connected to its vertices. Let us suppose that elements of two-terminal networks are introduced by their static characteristics by voltage.