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OPTIMAL CONTROL OF POWER FLOWS IN NON-UNIFORM ELECTRIC NETWORK WITH LONG-DISTANCE POWER TRANSMISSIONS

Improved mathematical model of non-uniformity of electric system (ES) with long-distance power transmissions of alternating current has been presented. Method of control impacts formation for regulating devices of such system has been suggested, the realization of such devices enables to provide maximum efficiency of electric energy transportation. The characteristic features of hardware-soft ware realization of local control of ES regulating devices, which provide the advantage of centralized control, are given.

Key words: *electric system, long-distance power transmission, non-uniformity, all-system index of non-uniformity, optimality conditions, optimal control.*

Introduction

One of the basic indices of efficiency of electric energy usage are technological charges, connected with energy transportation from supply sources to consumers. Analysis of actual expenses of electric energy in Ukraine, carried out in recent years [1], certifies the excess of corresponding indices, characteristic for the countries of Western Europe. Particularly, it concerns distributive electric systems, characterized not only by the constructive nonconformity to modern conditions of operation but also by negative influence from the side of electric networks, specified by their non-uniformity [2, 3].

Main reason of increased expenditures of electric energy, in particular, technical component of losses, is low efficiency of energy saving measures, that is due to low level of automation of monitoring and control of the mode of long-distance and distributive networks. Taking into account high level of the development of modern microprocessor systems and large-scale introduction of automated systems of modes monitoring, especially of electric networks, it becomes possible, first, to use the information from data bases of such systems in the problems of power flows control optimization [3] and interinfluence [4] of electric networks in the electric systems (ES) [4], second integrate subsystems of optimal control automation in automated control system (ACS).

Automation of power flows optimal control in modern ES, developing on the basis of existing ACS, provides the development and improvement of engineering, information and programming support. Nowadays, in the practice of energy systems dispatching control software – hardware facilities for optimization of ES normal modes are used, which have some drawbacks. Imperfection of mathematical software is connected, mainly, with the usage of simplified mathematical models of electric energy transport, which were actual 20 – 30 years ago and do not correspond to modern level of hardware development. In spite of constant development of the hardware in recent years, specialized information devices for communication between regulating devices of ES (transformers and on load tap-changing autotransformer) and controlled computers are practically missing and without such devices the interaction of programming facilities of electric networks mode optimal control and regulating devices (RD) is impossible. Besides, automated systems, providing localization of separate functions of centralized control, realizing programming control with local parameters and on-line correction of debugging parameters of local systems of automatic control (SAC), are able to improve the reliability of system operation and enlarge its functionality in special operation modes.

Thus, problems of improvement of software-hardware facilities of ES ASDC aimed at the realization of optimal control of their normal modes as a result of development of mathematical models and methods of PD parameters optimization as well as the facilities of such parameters realization, turned out to be of great importance.

Generalized indicators of ES non-uniformity

Negative impact of electric networks non-uniformity on the optimality of powers distribution in ES can be described by fictitious balancing electromotive forces $\dot{\mathbf{E}}_{bal}$, which lead to the emergence in closed contours balancing currents and to the deviation of the real current distribution I from economical $\dot{\mathbf{I}}_{ec}$ [2, 3]. For non-uniform electric networks, containing transformer couplings and long-distance power transmissions, e. m. f. can be determined by the expression [6]:

$$\dot{\mathbf{E}}_{bal} = \dot{\mathbf{N}}_{Ak}\dot{\mathbf{Z}}_B(\dot{\mathbf{I}} - \dot{\mathbf{I}}_{ec}), \tag{1}$$

where $\dot{\mathbf{N}}_{Ak}$ - is the matrix of ES branches couplings in its contours, constructed with the allowance of transformer couplings and long-distance power transmissions [6]; $\dot{\mathbf{Z}}_B$ - is the diagonal matrix of the resistances of equivalent circuit branches [6], where branches of long-distance power transmissions are represented by the constants of the two-port B [5, 6]; $\dot{\mathbf{I}}_{ec}$ - is the vector of economic currents in the branches of equivalent circuit of electric networks, determined on the basis of economic mode calculation of electric networks with long-distance transmission lines; I – is the vector of currents in the branches, that corresponds to real current distribution, taking into account the inter influence of electric networks of different classes of voltage, that operate in parallel.

In [6] it is shown that current distribution with minimal possible power losses in ES with long-distance transmission lines, that corresponds to economical mode of electric networks operation [2], can be calculated by r -equivalent circuit of ES (by analogy with [3]), on such conditions:

- active resistances of elements with concentrated parameters (short-distance transmission lines, transformers, etc.) and real parts of constant two-poles B (for long-distance transmission lines) are taken into account in equivalent circuit;
- transformation factors in closed contours are taken as balanced (e. m. f. of non-balance are missing);
- coefficients of wave propagation γ_0 [5, 7] and transmission line length correspond, so that in closed contours with long-distance transmission line e. m. f. of non-balance does not appear (constants of two-port $\dot{A}_i = ch(\gamma_{0i}\, l_i) = idem$).

Proceeding from the above-mentioned, the expressions for determination of vectors $\dot{\mathbf{I}}$ and $\dot{\mathbf{I}}_{ec}$, as functions of setting currents $\dot{\mathbf{J}}$ in the nodes of equivalent circuit of ES can be presented as:

$$\dot{\mathbf{I}} = \dot{\mathbf{Z}}_B^{-1}\dot{\mathbf{M}}_{Ak}^T(\dot{\mathbf{M}}_{Ak}\dot{\mathbf{Z}}_B^{-1}\dot{\mathbf{M}}_{Ak}^T)^{-1}(\dot{\mathbf{J}} - \dot{\mathbf{Y}}_b\dot{U}_b) + \dot{\mathbf{Z}}_B^{-1}\dot{\mathbf{M}}_b^T\dot{U}_b \ ; \tag{2}$$

$$\dot{\mathbf{I}}_{ec} = \mathbf{R}_B^{-1}\dot{\mathbf{M}}'^T_{Ak}(\dot{\mathbf{M}}'_{Ak}\mathbf{R}_B^{-1}\dot{\mathbf{M}}'^T_{Ak})^{-1}(\dot{\mathbf{J}} - \mathbf{Y}'_{Rb}\dot{U}_b) + \mathbf{R}_B^{-1}\dot{\mathbf{M}}'^T_b\dot{U}_b \ , \tag{3}$$

where $\dot{\mathbf{M}}_{Ak} = \mathbf{M}^+ + \mathbf{M}^-\mathbf{A}_d\widehat{\mathbf{K}}$ - is matrix of coupling of electric network branches in its nodes, taking into account ideal transformers and long-distance power transmissions [3, 6]; $\dot{\mathbf{M}}_{Ak}^T = \mathbf{M}^{T+} + \mathbf{K}\,\mathbf{A}_d\mathbf{M}^{T-}$ - is the transposed matrix of couplings of electric network branches in its nodes (symbol «^{T}» here and further denotes the operation of matrices transposition); $\mathbf{M}^{T+}$, $\mathbf{M}^{T-}$ - are matrices, formed by the change of negative or positive elements of transposed coupling matrix o $\mathbf{M}^T$ [2] by zero, correspondingly; $\mathbf{K}$, $\widehat{\mathbf{K}}$, $\mathbf{A}_d$ - are diagonal matrices of direct, complex conjugate. coefficients of transformation of transformer branches and constants of the two-pole A for other branches of equivalent circuit of electric network; $\dot{\mathbf{Y}}_b$, $\dot{\mathbf{Y}}_{Rb}$ - are columns of node conductance matrix corresponding to basic node of electric network, determined, correspondingly, by complete equivalent circuit and *r*-circuit; $\dot{U}_b$ - is voltage of basic node of electric network; $\dot{\mathbf{M}}_b^T$ - is the column of couplings matrix corresponds to basic node of electric network; $\mathbf{R}_B$ - is diagonal matrix of branches resistances, containing only active components of branches $\dot{\mathbf{Z}}_B$ resistances; $\dot{\mathbf{M}}'^T_{Ak}$, $\dot{\mathbf{M}}'_{Ak}$, $\dot{\mathbf{M}}'^T_b$, $\mathbf{Y}'_{Rb}$ - are matrices of couplings and passive parameters of equivalent circuit of electric network, determined with allowance of the conditions of economical mode calculation, presented above.

Having substituted in (1) the expressions for $\dot{\mathbf{I}}$ and $\dot{\mathbf{I}}_{эк}$ after conversions and reductions we obtained:

$$\dot{\mathbf{E}}_{bal} = \dot{\mathbf{N}}_{Ak}\left(\dot{\mathbf{M}}_б^T - \dot{\mathbf{M}}'^T_b\right)\dot{U}_b - j\dot{\mathbf{N}}_{Ak}\mathbf{X}_B\mathbf{R}_B^{-1}\left[\dot{\mathbf{M}}'^T_{Ak}(\dot{\mathbf{M}}'_{Ak}\mathbf{R}_B^{-1}\dot{\mathbf{M}}'^T_{Ak})^{-1}(\dot{\mathbf{J}} - \mathbf{Y}'_{Rb}\dot{U}_b) + \dot{\mathbf{M}}'^T_b\dot{U}_b\right] = \dot{\mathbf{E}}'_{bal} - j\dot{\mathbf{E}}''_{bal} \quad (4)$$

where $\mathbf{X}_B$ - is diagonal matrix of branches resistances, containing only reactive components of branches $\dot{\mathbf{Z}}_B$ resistances.

By definition matrices-columns $\dot{\mathbf{M}}_b^T = \dot{\mathbf{M}}'^T_b$, i. e., component $\dot{\mathbf{E}}'_{bal} = 0$. Hence, (4) can be presented in the form:

$$\dot{\mathbf{E}}_{bal} = -j\left(\dot{\mathbf{N}}_{Ak}\mathbf{X}_B\mathbf{R}_B^{-1}\dot{\mathbf{M}}'^T_b\dot{U}_b + \dot{\mathbf{N}}_{Ak}\mathbf{X}_B\mathbf{R}_B^{-1}\dot{\mathbf{M}}'^T_{Ak}(\dot{\mathbf{M}}'_{Ak}\mathbf{R}_B^{-1}\dot{\mathbf{M}}'^T_{Ak})^{-1}(\dot{\mathbf{J}} - \mathbf{Y}'_{Rb}\dot{U}_b)\right), \quad (5)$$

or in relative units in reduction to the voltage of basic node:

$$\dot{\mathbf{E}}_{bal*} = -j(\dot{\mu}_{1*} + \dot{\mu}_{2*}); \; \dot{\mu}_{1*} = \dot{\mathbf{N}}_{Ak}\mathbf{X}_B\mathbf{R}_B^{-1}\dot{\mathbf{M}}_b^T; \; \dot{\mu}_{2*} = \dot{\mathbf{N}}_{Ak}\mathbf{X}_B\mathbf{R}_B^{-1}\dot{\mathbf{M}}'^T_{Ak}(\dot{\mathbf{M}}'_{Ak}\mathbf{R}_B^{-1}\dot{\mathbf{M}}'^T_{Ak})^{-1}\mathbf{Y}_l, \quad (6)$$

where $\mathbf{Y}_l = (\dot{\mathbf{J}}\dot{U}_b^{-1} - \mathbf{Y}'_{Rb})$ - is the vector of loads conductances, with allowance of mutual conductances of the basic node. Vectors $\dot{\mu}_{1*}, \dot{\mu}_{2*}$ are determined by the relation of reactive and active resistances of equivalent circuit branches, transformation factors of the transformers and constants of two-pole of long-distance transmission lines *A*, i. e., are generalized indices of non-uniformity of electric network. Proceeding from (6), the lack of balancing e. m. f. in closed contours is a characteristic feature only for electric networks, where all branches correspond to classical condition of uniformity [2], $x_i/r_i = idem$ (necessary condition - $\dot{\mu}_{2*} = 0$), and transformation factors in the contours are balanced and for long-distance transmission lines the condition of matching of wave propagation coefficients is provided $\gamma_i = \sqrt{(r_i + jx_i)(g_i + jb_i)} = idem$ [5] (sufficient condition - $\dot{\mu}_{1*} = 0$). Proceeding from the latter statement, it is practically impossible to provide the uniformity of electric networks with long-distance transmission lines by project measures, especially, taking into account considerable dependence of their cross-sectional conductances g_i, b_i , on random impact of the environment. To provide operation modes, close to economical ones, it is expedient to use measures aimed at optimal control of coupling transformers with longtitudinal-cross-sectional regulation.

Method of formation of optimal control laws of power flows in electric systems, based on the analysis of their non-uniformity

As it is known [3] it is possible to compensate additional losses of power and electric energy in

ES, caused by its non-uniformity [2, 3], by means of regulation of voltage in ES nodes or by introduction balancing e. m. f. in the contours. In this case, e. m. f are controlled variables, which are to be introduced in closed contours for realization of optimal current distribution [3] as a result of changing of transformation factors of the transformers, making part of these contours.

In [3] it is shown, that optimal value of losses in ES is achieved at relative values of e. m. f., calculated by the formulas:

$$\mathbf{E}_{*bal.a}(t) = \pi_a^E \mathbf{J}_{*_r}(t), \quad \mathbf{E}_{*bal.r}(t) = \pi_r^E \mathbf{J}_{*_a}(t), \tag{7}$$

where $\mathbf{E}_{*bal.a}(t), \mathbf{E}_{*bal.r}(t)$ - are vectors of active and reactive components of relative values of balancing e. m. f.; $\mathbf{J}_{*_a}(t), \mathbf{J}_{*_r}(t)$ - are vectors of active and reactive components of relative values of currents in the nodes of ES; $\dot{\mathbf{J}}(t) = \widehat{\mathbf{U}}_d^{-1}(t) \cdot \widehat{\mathbf{S}}(t)$ - is the vector of node currents of ES (symbol «^» here and further denotes complex-conjugate .values of complex magnitudes); $\widehat{\mathbf{U}}_d(t)$, $\widehat{\mathbf{S}}(t)$ - is diagonal matrix of nodal voltages and vector of nodal powers; π_a^E, π_r^E - are matrices of similarity criteria.

In (7) all the parameters are presented in relative units. Parameters of ideal mode, calculated by *r*-equivalent circuit of ES are taken as basic ones.

Matrices of similarity criteria are determined by the formulas [3]:

$$\pi_a^E = -\left[\mathbf{E}_{bal.a}^{(b)}\right]_d^{-1} \nu \mathbf{r}_в \mathbf{M}_\alpha^{-1} \left[\mathbf{J}_r^{(b)}\right]_d; \qquad \pi_r^E = \left[\mathbf{E}_{bal.r}^{(b)}\right]_d^{-1} \nu \mathbf{r}_в \mathbf{M}_\alpha^{-1} \left[\mathbf{J}_a^{(b)}\right]_d , \tag{8}$$

where $\nu = \mathbf{N}_\alpha \mathbf{x}_{в\alpha} \mathbf{r}_{в\alpha}^{-1} - \mathbf{x}_c \mathbf{r}_c^{-1} \mathbf{N}_\alpha$ - is the matrix of system indices of ES non-uniformity; $\mathbf{r}_c, \mathbf{x}_c$ - active and reactive components of contour resistances matrix for the system of basic contours; $\mathbf{M}_\alpha, \mathbf{N}_\alpha$ - are coupling matrices of the branches of ES equivalent circuit tree , in nodes and contours, correspondingly .

Relations (7) are laws of optimal control, where feedback coefficients in physical sense, are similarity criteria. For realization of control laws, according to (7), the system of automatic control (SAC) of ES normal modes, was developed [3, 4], main function of the system is to maintain the value of complex optimality criterion *F**, that takes into consideration the factors of reliability and economic efficiency of electric energy transportation as well as its quality [3, 4], within the limits of the established non-sensitivity zone δF^* (control impacts by the regulating devices are performed when the criterion leaves the zone). The result of system operation is the approaching of the current path of power losses change in ES to optimal path by preset operation conditions [3]. Besides, as it is shown in [4], realization of control impacts, obtained at the base of (7), provides optimization of mutual influence of transmission lines and distributive electric systems by losses and voltage levels.

However, to obtain (7) and (8) a number of assumptions has been mode. Reduction of electric networks parameters with transformer couplings to one class of voltage and, correspondingly, the impossibility of account of non-balanced transformation coefficients in ES contours, calculation of capacitance generation and corona losses for transmission lines (TL) with nominal voltages, modeling of long-distance transmission lines modes without account of their wave properties may have negative impact on the adequacy of reproduction of optimal states of ES and lead to realization of inefficient decisions.

Improvement of the method of the formation of optimal control laws of electric systems with long-distance power transmission normal modes

For compensation of negative impact of ES non-uniformity parameters at the expense of RD control non-balance e. m. f. are to be introduced in the contours $\dot{E}_{nb} \to -\dot{E}_{bal}$, as a result, non-balance currents $\dot{I}_{nb}$ partially or completely compensate fictitious balancing currents $\dot{I}_{bal}$ [3]. In general case for j^{th} contour, belonging to the system of basic contours [2, 3] non-balance e. m. f. is determined:

$$\dot{E}_{nb_j} = \left(1 - \prod_{i \in \mathbf{TP}_j} \dot{k}_i\right)\dot{U}_b \ , \tag{9}$$

where $\dot{k}_i$ - is transformation coefficients of i^{th} transformer, belong to the set of transformers of j^{th} contour $\mathbf{TP}_j$; $\dot{U}_b$ - is voltage of basic node of ES.

Fictitious balancing e. m. f. in non-uniform electric networks, containing transformer couplings and long-distance power transmission as the functions of natural and economical current distribution, can be determined by the expression (1). Expressions for vectors determination (3) if some balancing nodes in electric networks are available, can be presented in the following way [6]:

$$\dot{\mathbf{I}} = \dot{\mathbf{Z}}_B^{-1}\dot{\mathbf{M}}_{Ak}^T(\dot{\mathbf{M}}_D\dot{\mathbf{Z}}_B^{-1}\dot{\mathbf{M}}_{Ak}^T)^{-1}(\dot{\mathbf{J}} - \dot{\mathbf{Y}}_b\dot{\mathbf{U}}_b) + \dot{\mathbf{Z}}_B^{-1}\dot{\mathbf{M}}_b^T\dot{\mathbf{U}}_b \ ; \tag{10}$$

$$\dot{\mathbf{I}}_{ec} = \mathbf{R}_B^{-1}\dot{\mathbf{M}}_{Ak}^T(\dot{\mathbf{M}}_D\mathbf{R}_B^{-1}\dot{\mathbf{M}}_{Ak}^T)^{-1}(\dot{\mathbf{J}} - \mathbf{Y}_{Rb}\dot{\mathbf{U}}_b) + \mathbf{R}_B^{-1}\dot{\mathbf{M}}_b^T\dot{\mathbf{U}}_b \ . \tag{11}$$

Having substituted in the expression of balancing e. m. f. (1) expressions for $\dot{\mathbf{I}}$ and $\dot{\mathbf{I}}_{ec}$ after transformations and simplifications we obtained:

$$\dot{\mathbf{E}}_b = \dot{\mathbf{E}}_{*nb.k}\dot{\mathbf{U}}_b - j\left(\dot{\mathbf{E}}_{*nb.\gamma}\dot{\mathbf{U}}_b + \dot{\mathbf{Z}}_{f.b}\dot{\mathbf{J}}\right), \tag{12}$$

where $\dot{\mathbf{E}}_{*nb.k} = \dot{\mathbf{N}}_{Ak}\dot{\mathbf{M}}_b^T$ – is the matrix of relative contour e. m. f., determined by non-balanced transformation coefficients and the coefficients of long-distance transmission lines propagation (j^{th} element $\dot{E}_{*nb.j}$ corresponds to the expression (9)); $\dot{\mathbf{E}}_{*nb.\gamma} = \dot{\mathbf{N}}_{Ak}\mathbf{X}_B\mathbf{R}_B^{-1}\left(\dot{\mathbf{M}}_b^T - \dot{\mathbf{M}}_{Ak}^T(\dot{\mathbf{M}}_{Ak}\mathbf{R}_B^{-1}\dot{\mathbf{M}}_{Ak}^T)^{-1}\mathbf{Y}_{Rb}\right)$ - is the matrix of relative contour e. m. f., determined by transfers of power between balancing sources of electric energy and depends on the non-uniformity of the system; $\dot{\mathbf{Z}}_{f.b} = \dot{\mathbf{N}}_{Ak}\mathbf{X}_B\mathbf{R}_B^{-1}\dot{\mathbf{M}}_{Ak}^T(\dot{\mathbf{M}}_{Ak}\mathbf{R}_B^{-1}\dot{\mathbf{M}}_{Ak}^T)^{-1}$ – is the matrix of fictitious contour resistances, determines balancing e. m. f. as the function of non-uniformity of longitudinal and transversal parameters of ES.

It is seen from (12) that components $\dot{\mathbf{E}}_{*nb.\gamma}$ and $\mathbf{Z}_{f.b}$ are determined by the relation of reactive and active resistances of equivalent circuit branches of ES, transformation factors of the transformers and propagation coefficients of long-distance power transmissions (in the form of constants of two-pole *A*). Thus, as it is shown above, the lack of balancing e. m. f. in closed contours is a characteristic feature only of electric networks, where transformation factors in the contours are balanced, all the branches correspond to classical condition of uniformity [2], and for long-distance transmission lines the condition of matching of wave propagation coefficients is provided. Proceeding from the above-mentioned, it is practically impossible to provide the uniformity of electric networks with long-distance transmission lines, and to provide operation modes, close to economical ones optimal control of coupling transformers with longitudinal-transversal regulation is required.

For the case of ES with a single basic node $\dot{\mathbf{E}}_{*nb.\gamma} = 0$, and e. m. f. of non-balance are determined only by non-balance transformation coefficients. Optimal correction of the given parameters by RD provides meeting of condition of economical current distribution in ES and, correspondingly, power transfers and inter influence of electric networks of different voltage classes ($\dot{\mathbf{E}}_b \to 0$).

If the problem of ES flow distribution optimization is set with several balancing sources of electric energy, then the component, determined by power flow between sources $\dot{\mathbf{E}}_{*nb.\gamma}\dot{\mathbf{U}}_b$ is added to nonbalance e. m. f. Thus, balancing e. m. f. can be compensated, besides the method, mentioned above, by means of voltage regulation in the centers of supply (change of reactive and active power generation in ES).

Conditions for economical current distribution $\dot{\mathbf{E}}_b = 0$, proceeding from (12) can be presented as:

$$\dot{\mathbf{E}}^{opt}_{nb.k} = j\left(\dot{\mathbf{E}}_{*nb.\gamma}\dot{\mathbf{U}}_b + \dot{\mathbf{Z}}_{f.b}\dot{\mathbf{J}}\right), \tag{13}$$

where $\dot{\mathbf{E}}^{opt}_{nb.k} = \dot{\mathbf{E}}^{opt}_{nb.k}\dot{\mathbf{U}}_b$ - is the vector of optimal contour e. m. f. of nonbalance, which by their physical nature can be realized by means of RD parameters changing. Optimal value of transformation factor of regulating transformer $\dot{k}^{opt}_0$ for j^{th} basic contour, starts with i^{th} basic node, proceeding from (9), taking into account the impact of propagation factors of long-distance transmission lines [6], can be calculated by the expression:

$$\dot{k}^{opt}_0 = \left(1 - \dot{E}^{opt}_{*nb.k_j}\right) \Bigg/ \left(\prod_{s\in \mathbf{TP}_j; s\neq 0} \dot{k}_s \cdot \prod_{s \in \mathbf{DL}_j} \dot{A}_s \right), \tag{14}$$

where $\dot{A}_s$ - is the constant of two-pole for s^{th} transmission line [6], that makes part of the set of long-distance lines of the j^{th} contour $\mathbf{DL}_j$.

Hence, using the expressions (13), (14) we can define optimal transformation factors of regulating transformers, taking into account changes of consumers load, planned generation of electric energy sources and consequences of primary regulation of voltage. Unlike (7), in (13), (14) the influence of the characteristics of the process of electric energy transportation by long-distance transmission lines are taken into account, that increases the adequacy of decisions, regarding optimal control of ES normal modes.

Characteristic features of the realization of the system of automatic control of power flows in ES with decentralized control function in real-time

For the realization of the system of automatic control of power flows and voltage in electric systems, that would provide the possibilities of on-line control according to (13), (14), it is expedient to use classical two-contour scheme [3, 4] with decentralized control function in real time. At the first stage (in the contour of centralized control) the reasons of non-optimal ES operation and the list of available regulating devices are determined. For this purpose, retrospective analysis of modes control results, based on short term planning is performed and ES non-uniformity indices are evaluated. Then, using the complete information, regarding ES parameters, matrices of conventionally stable parameters, making part of (13) are determined and corrected. Using the elaborated mathematical models [3, 4], the adaptation of control laws in real conditions of regulating devices operation is carried out, ranking of regulating devices by the priority of control, taking into account reliability and resources of on-load tap-changing devices is performed. Non-sensitivity zones of local control systems of regulating devices, enabling to establish rational intensity of switchings for each transformer and coordinate their operation during on-line control in such a way that the reduction of power losses could be achieved at minimum number of switchings.

At the second stage (in the contour local control) the obtained mathematical models (13) are used for determination of calculated value of control impacts (14) and decision making regarding expediency of their realization. Control during the process is carried out only in the contour of on-line control. In the external contour, if necessary, the correction of ES passive parameters for (13) can be realized. However, such variation is realized, as a rule, at the stage of short-term planning of modes, after essential changes of loads or considerable deviations of regulating devices parameters from planned ones [4].

Similar scheme of control system realization allows to provide the decentralization of the part of information functions, without loosing the principles of centralized control, since during basic time (ES normal operation modes) regulation of transformers parameters is carried out on the basic of local parameters, providing conventional optimum of system optimality criterion [3, 8]. Deviation of ES passive parameters or mode parameters is controlled from the single source and if necessary, separate parameters of the models (13) and (14) are corrected. Thus, centralized on-line control of ES modes is realized by means of "decentralized" subsystems – local regulating devices at separate transformation substations (electric plants).

Automatic control of RD of ES and matching of control impacts with on-line control is performed using microprocessor unit of automatic monitoring and operation control (AMOC) RD [8] (Fig. 1). The device can operate in three basic modes:

1) Receiving of the law from the host computer and control according to it (if reliable information regarding the state of electric network is available);

2) Introduction from the central control system the number of a tap and its installation on the regulator of on-load tap-changing of the transformer (if corresponding information support or remote control of energy system dispatcher is missing);

3) Autonomous operation of the device in secondary voltage of the transformer stabilization mode or autotransformer at preset level, taking into account the introduced zone of non-sensitivity or autonomous realization of counter regulation of the voltage.

Fig. 1. External view of AMOC RD device (front view)

For switching of AMOC RD from the wait state into active state, operation code is transferred by means of ACS of the substation across communication unit. After that the device verifies the on-load tap-changing parameters for identification of the extreme positions – the obtained information is written into RAM. Depending on the code of operation the device is shifted in corresponding operation mode.

If it is necessary to determine certain tap of the regulator, its number is input across communication unit from the host computer. If the number of a new tap does not coincide with the number of already installed one, the sign of control signal (direction of on-load tap changing) is determined. Then the control pulses arrive at the registers of control unit and monitoring of on-load tap-changing regulator; corresponding relays close and switching starts. The device passes into wait mode of switching termination, controlling corresponding channels of control and monitoring unit. After termination of switching control pulses are eliminated, parameters of the object of control are measured, their correspondence to preset limitations are checked and numbers of taps are compared again. The process is repeated until the needed tap is installed at the regulator. Any violations of limitations by parameters (currents, voltage), faults of device or regulating unit in the form of messages are sent to host computer.

On-line control of ES modes is carried out by means of "АЧП" programs complex [3, 8] and AMOC RD device. In order to adapt the laws of control and registration of technical limitations of the regulated transformer by the levels of voltages and transformation factors, observation vector is specified by means of measurement of mode parameters (currents and voltages) directly on regulated transformer. Such approach enables to increase the stability of control to variation of external factors and realize it in automated or automatic manner within the frame of existing ASDC [8].

Hence, in case of automatic control by the law (13), first, the check of the necessity of ES passive parameters specification. If the changes are registered, then their updating is realized from the host computer. Then, the programme-driver generates the inquiry for AMOC RD for the change of local parameters of electric network, serving for specification of data, obtained from database of ES on-line information complex of ES. Using the given information, in accordance with the law of control (13), optimal values of transformation factor (14) and the number of RD tap to be installed, are determined.

Application of AMOC RD enables to introduce the feedback in the system of ES normal modes control, monitor the realization of control impacts and evaluate the efficiency of control both of separate transformers and energy system. The latter gives the possibility to automate a number of functions of on-line control and improve the efficiency of transformers RD usage in the problems of the decrease of active power losses in the electric system.

Conclusions

1. Electric systems are not optimal, taking into account energy charges in the process of its generation, transportation and distribution. One of the main reasons of non-optimality of ES states is their non-uniformity. The given research has solved the problem of the development of the method intended for determination of generalized index of ES non-uniformity, containing long-distance transmission lines. Proceeding from the suggested mathematical model of electric networks non-uniformity, taking into account the characteristic features of long-distance transmission lines operation it is shown that for such networks their uniform state can not be provided due to non-stability of longitudinal and transversal parameters. Thus, in order to provide their modes optimality, the application of corresponding automatic control systems is required.

2. For the solution of the problem of the laws of optimal control ES coupling transformers determination, taking into account the characteristic features of their impact on the process of the transport and distribution of electric energy in long-distance transmission lines the mathematical model of optimal e. m. f. of non-balance and the method of optimal transformation factors of RD, that takes into account wave properties of long distance transmission lines, impact of non-balanced transformation factors of coupling transformers and voltage regulation in ES supply centers, were suggested. Such improvement enables to take more efficient decisions in the problems of optimal control of power flows and voltage in ES.

3. Application of AMOC RD unit allows to realize in automated system of optimal control of ES normal modes the feedback by control parameters and provides the possibility of decentralization of certain problems of optimal control, such as, adaptation of monitoring parameters, control over the realization of control impacts, evaluation of the expediency of separate transformers control, etc. The latter enables to increase the reliability and the efficiency of regulating devices usage in ES.

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