Chapter

Determination of Optimal Transformation Ratios of Power System Transformers in Conditions of Incomplete Information Regarding the Values of Diagnostic Parameters

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Abstract

On the base of damage rate analysis of power transformers and methods of electrical energy system (EES) modes control the necessity of using the results of on-line diagnostics of LTC transformers not only for determinations of the expending of further operation or equipment repair but also for calculation of optimal transformation coefficients (with account of the suggested RRCT) for their application in the process of modes control has been proved. Improved method of determination of control action, realized by the LTC transformers by means of comparative analysis of the results calculation of EES modes with quasi resistances of the circuit branches. Such peculiarity of the suggested method of determination of control actions by LTC transformers, as the account of RRCT, in the process of EES mode control provides such advantages as reduction of the damage rate of the equipment, reduction of active power losses in EES. Due to the peculiarities of the method of determination of control actions by LTC transformers, with the account of their technical state, perspectives of the development and introduction in EES modern microprocessor-based systems of automatic control of transformers LTC open.

Keywords: on-line diagnostics, control, normal modes, active power losses, similarity theory, neuro-fuzzy modeling, basic similarity criteria, membership functions, uncertainty

1. Introduction

Characteristic feature of present day situation are the attempts of utility companies to increase energy efficiency in conditions of continuing aging of high voltage equipment.

Practice of large-scale introduction of the intelligent support of decision making of solution processes proves their efficiency. One of the directions of efficiency increase of electric energy transportation is improvement of methods and means of active power losses reduction on conditions of maintaining reliable operation of high voltage equipment, including outdated equipment.

The set of electric energy system (EES) states and the processes of transition from one state into another her is EES mode (further-mode), characterized by the parameters, for instance, electrical voltages an substations loads, currents in transmission lines transformation ratios of the transformers, etc., normal operation mode 07 of EES modes. Control by the system of on-line dispatching control (LDC). Modern LDS technologies, for instance, provided by smart grids concept, are aimed at improvement of its information support. This enables the optimal implement more efficiently energy-saving technologies in electric systems, when out of date high-voltage equipment is using.

Means of similarity theory, in particular the criterion method (KM), can effectively solve and analyze optimization problems [1]. Criteria-based method can be defined as a set of techniques and principles, according to which the analysis, comparison and interpretation of baseline data to provide scientific and practical conclusions. The ultimate goal of studies using the criterial method is to reveal regularities, which under certain conditions can be represented as the law control [2]. The main purpose of KM is to find the variant of the process or the object. Most often, in the further analysis, the parameters are used as reference. According to his idea, KM is close to the geometrical programming [3]. This use of duality of optimization problems is the replacement of the direct problem for the corresponding dual. The main difference is that the basis for geometric programming is inequality between geometric and arithmetic averages, and the background of the KM—matrix properties of dimensions or indicators [4]. This is the meaning of dual variables. In geometric programming are weighting factors, in KM—similarity criteria. That is, the result of solving the tasks of the KM is values of criteria of similarity or, in other words, the optimum ratio of the individual parameters, and not they themselves. This specific feature characteristic only of KM, determines its scope.

2. Analysis of the literature data and problem set up

In [5] the technique of voltage drop decrease in separate parts of distribution electric grids is, suggested, but it does not take into account technical state of regulating devices [6]. In [7] on the example of Indian electric grids the statistics of the increase of power, transmitted in electric grid is considered.

It is stated that in order to improve the grid reliability and efficiency of energy transmission it is necessary to use power transformers, equipped with LTC and automatic or automated control systems for such LTC control. It enables to control power flows in EES by means of LTC so that the parameters of electric grids modes were within the limits of normal values of equipment (transmission lines, switching devices, transformers, etc.) parameter.

It is provided by usage of FACTS technologies. For instance, in [8], the possibilities of using phase-shift transformer for power flows change in electric energy system to reduce power losses in the process of energy transmission in transmission lines of Slovak Republic are considered. In [9] high price of FACTs technologies usage in energy branch for the reduction of electrical power is proved. In [10] three variants of power flows control in electric grid, using three FACTs devices are considered with Thyristor Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC) and phase-shift transformer (PST), but in [11] any attention is paid to the state of equipment, used for modes control. In [12] the conclusion is made that prolongation of power transformers operation term for

20–30 years is more profitable than their replacement by new ones, and the quantity of power transformers in the USA, that have been in operation for more than 25 years (certificate resource – 25 years) is approximately 65%.

In [13] attention is paid to the system of continuous monitoring of technical state of power transformers, the given system is used at the transformers of joint-stock company "Magnitogorsk Metallurgical Complex", HYDRAN analyzer, methods of localization and identification of faults, practical necessity of partial discharges control is underlined, but the results of diagnostics during modes control are not paid attention to.

In [14] it is noted that in local electric system in order to provide stable operation and indices of electric energy quality it is necessary to use modern control systems that take into consideration voltages in nodes and frequency and eliminate emergency deviations. At the same time, in [15] modeling of non-stationary critical operation modes of EES in the process of parameters change in wide limits by means of application of non-linear mathematical models attention is paid to. This enables to study the consequences of such modes, promptly take measures, aimed at their prevention or elimination. In pages [16] technical state of the equipment of these systems is not taken into account, this can lead to the damage of the equipment and undersupply of energy to the consumers.

Thus, the problem of development of the methods of diagnostics results account during control of EES modes is not solved.

It is known that operation control (RTOC) in Ukraine is carried by a man. Overloading of this person with a great volume of diagnostic parameters data, especially in conditions of limited time for decision-making, leads to their actions. In the process of modes on-line control, especially post-occident modes. It is expedient to assess the state of equipment by generalized indices, for instance, by residual resources coefficient of the transformers (RRCT). The development of the method of on-line diagnostics of the transformers and the account of RRCT in the process of ESS modes control for minimization of total losses of active power are not considered in literature sources and is the subject of authors study.

3. Objectives and tasks of the research

The objective of the research is the development of the method of diagnostics of the transformers with LTC and account of PRCT values in the process of EES modes control for minimization of active power losses. To realize this objective the following problems are to be solved:

- substantiate the expediency of applying the results of diagnostics of LTC-transformers in the process of optimal control of EES modes;
- develop neuro-fuzzy model of residual resource coefficient of the transformers (RRCT);
- develop the method of RRCT values and power transformers with LTC state account in the process of EES modes control.

4. Materials and methods of transformers diagnostic study

Automation of the process of power flow control may be provided by means of centralized remotely controlled alternative usage of switching devices (LTC) of the transformers. Under such conditions, there appears the possibility of the analysis of control actions of separate LTC on mode parameters of EES by means of the feedback. This approach improves the operation quality of adaptive control automatic systems of the LTC position control. For this purpose, at considerable changes of load schedule it is necessary to perform ranking of the transformers with LTC by the quality of their impact on maintaining parameters of the modes.

Realization of measures, aimed at reduction of power losses is limited by the possibilities of the equipment involved in the provision of mode; namely, by its technical state. It is known, that the damage of high voltage equipment during mode control (for instance, power transformers) leads to losses, which considerably exceed the cost of electric energy, saved as a result of losses decrease. Failure rate of the outdated high voltage equipment (power transformers, shunting reactors, instrument current and voltage transformers, switches, etc.) increases, when such equipment has been in operation for more than 25 years [17]. Taking into consideration the fact that the control of EES modes is accompanied by the operation of switching devices, regulation devices of transformers, emergence of switching surges, ferro-resonances, currents increase in power and instrument transformers, transmission lines, etc., then the control of modes must be realized, taking into consideration their technical state [18] and possible expenses for their replacement or repair.

Thus, it is necessary to know current state of high voltage electric equipment of EES, which is in operation during modes control.

5. Determination of current technical state of power transformers

We will consider the method of determination of power transformers current state and RRCT values in the process of EES modes control on the example of power high voltage transformers, which have on-load-tap changing device.

We suggest to evaluate technical state of power transformer by means of the analysis of the value of its residual resource coefficient. Power transformer residual resource coefficient has the dimensionality in relative units and can change in the process of operation in the range from one (the best technical state) to zero (the worst technical state, when the transformer must be removed out of service for inspection, repair, replacement, etc.).

Then, we will consider the example of residual resource coefficient determination of the transformer ATDCTN 125000–330/110. First we will study the statistics of failure rate of such transformers. **Table 1** contains the example of possible reasons and amount of transformers removal out of service, that is close to data, published in studies [19].

In **Table 1** such symbols are used: Z_k is the resistance of the transformer windings (during measurements in short – circuit mode); t° is the temperature of contact points (for instance, bushing of the bus duct or with winding lead); $P_{i.p.}$ idle mode power, that characterizes the quality of magnetic circuit; R_{in} is the resistance of the insulation for revealing the contamination and aging of solid and liquid insulation (also it is necessary to determine the capacity and dielectric loss tangent, also it is desirable to determine the degree of polymerization); W humidification of the isolation; $k_{resid.res.bush}$ or k_{bush} is the residual resource coefficient of the bushings; $CADG_C$ is residual resource coefficient of the transformer by the results of chromatographic analysis of dissolved gas in the transformer oil of the tank and LTC (ethylene, ethane, methane) of the transformer, that characterizes oil contamination by the gases, dissolved in it and among them acetylene and hydrogen (for revealing of discharges); PCA residual resource coefficient of the transformer by the results of physical–chemical analyses of transformer oil from transformer tank,

Transformer element	Designation	Parameter name	Units	%
Windings	Z_k	Winding deformation	8	1.6
	t^0	Deterioration of contact joints state	10	2
	$P_{i.p}$	Idle power that characterizes of the magnetic quality	15	3
Insulation	$R_{in}R$	Contamination of isolation	65	13.4
	W	Humidification of the isolation	48	10
Bushings	k_{bush}	Defects of bushings	74	15.2
Oil	$CADG_c$	Content of dissolved gases	71	14.6
	PCA	High moisture content and deviations of other parameters of the oil	43	9
	$CADG_d$	Discharges in oil	64	13.2
LTC	$k_{def.LTC}$	LTC defects	45	9.3
Cooling system	I_{motor} or I_{mt}	The current of oil pump drive motor	14	2.9
	t^o_{cool}	Coolers temperature	16	3.3
Tank	k_{tank}	Tank leakage	12	2.5
Total			485	100

Table 1.
Reasons of removing out of service power transformers.

contactor and LTC tap changer; $CADG_d$ is residual resource coefficient of the transformer by the results of chromatographic analysis of the dissolved hydrogen and acetylene in the transformer oil of the tank and LTC of the transformer tap changer in order to reveal the discharge; $k_{def.LTC}$ or k_{LTC} coefficient of the transformer LTC residual resource; I_m is the current of electric motors oil pumps and fans of cooling system; $t°_{cool}$ is coolers temperature; k_{tank} is the residual resource coefficient of the transformer tank, determined by the availability (takes the value "0") or absent of oil leakage (takes the value 1).

From **Table 1** shows that the transformers are often displayed in repairs due to moisture and oil contamination, insulation and high-voltage inputs defects.

The task of creating a mathematical model complicated with incomplete initial data as part of the parameters known at the time of payment, such as the reasons for the need for additional studies. To establish reciprocal links diagnostic parameters very constructive simulation technology is unclear. This simulation allows to obtain more reliable results compared to the results of existing diagnostic systems.

In **Table 1** under the term the controlled diagnostic parameter we mean the parameter deviation of which from the norm helped to remove the transformer out of service or was taken into account in the process of its removal out of service. In **Table 1** the following diagnostic parameters are given: parameters, that characterize the state of the windings, insulation, bushings, oil, LTC, cooling systems, tank.

Having analyzed the data of **Table 1** the scheme was created that shows whether dependent or independent is the impact of diagnostic parameters on the coefficient of total residual resource of the transformer (**Figure 1**).

Figure 1 does not show mutual impact of one controlled diagnostic parameter on the other one; it is shown either in dependent or independent manner how these parameters influence the coefficient of total residual resource of power transformer (PT).

In **Figure 1** over the parameter the percentage amount of revealed faulty transformers by the given parameter is shown, that is given in percent from the total amount of faulty transformers.

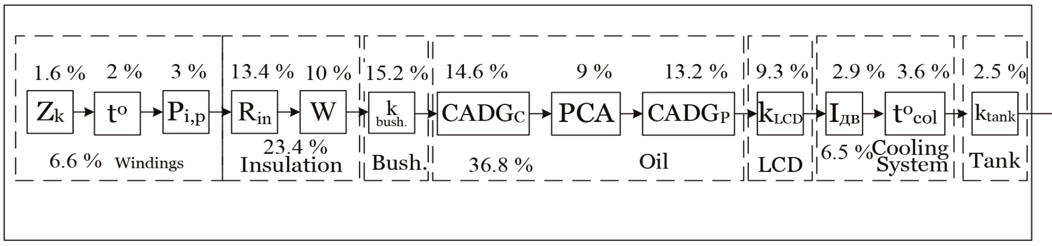

Figure 1.
Structural diagram of the model of total residual resource coefficient of the transformer.

The blocks with parameters whose deviations from the norm substantiate the necessity of the output of the transformers for repair, are shown sequentially and are shown k_{res} – residual resource coefficient of the transformer (RRCT). In parallel, blocks with parameters are also depicted. A large change in these parameters proves the necessity of outputting a power transformer (PT) for repair. PT is repaired in case of deviation from the norms of these parameters. This is due to the requirements for the reliability of the transformers. In each of the given blocks parallel can be allocated but it are not shown to simplify the calculation (for instance, currents of electric motors of oil pumps and fans).

In order to obtain the generalized parameter of the residual resource of the transformer, it is proposed from the known values of diagnostic parameters to pass to the corresponding values of residual resources coefficients (in relative units) by each diagnostic parameter. This will allow you to take into account the value of all diagnostic parameters and the impact of each of them.

These coefficients are defined in relative units by (1) and that is why they characterize total output of the transformers from the moment of their technical state control to transition to boundary state that is residual technical resource (12). Residual resource coefficient k_{i_1} by i_1th diagnostic parameter:

$$k_{i_1} = \left| \frac{x_{i_1,\lim} - x_{i_1,cur}}{x_{i_1,\lim} - x_{i_1,in}} \right|, \tag{1}$$

where $x_{i_1,\lim}$ is admissible limit normative value of i_1^{th} diagnostic parameter; $x_{i_1,cur}$ is value of i_1^{th} diagnostic parameter at the moment of control; $x_{i_1 in}$ is initial value of i_1^{th} diagnostic parameter (at the moment of putting into operation of new equipment or after repair), i_1 is number of diagnostic parameter.

We perform the reduction of the circuit by the following expressions. For serial part of the circuit (**Figure 1**) the coefficient of total residual resource is found by the expression:

$$\mathrm{k_{tot.resid.res.}} = \prod_{\tau=1}^{\nu} \mathrm{k}_{\tau}^{\mathrm{p}_{\tau}}, \tag{2}$$

where k_τ is the coefficient of residual resource of PT by τ^{th} diagnostic parameter; τ is τ^{th} diagnostic parameter; ν is the amount of blocks in the serial part of the circuit of **Figure 1**, p_τ probability of control parameters deviator from maximum permissible normalized value of this parameter is found by means of the expression (3):

$$\mathrm{p}_{\tau} = \frac{\mathrm{y}_{\tau}}{\mathrm{m}_2}, \tag{3}$$

where y_τ is a number of controlled parameter deviations from admissible limiting normalized value of this parameter, which were revealed by means of τth diagnostic parameter control (τ for serial part of the circuit) from the total number of the revealed deviations of controlled parameters from admissible limiting normalized value; m_2 is total quantity of the revealed deviations of controlled diagnostic parameter from their admissible limiting normalized values.

For parallel part of the circuit the coefficient of total residual resource is found by the expression (4)

$$k_{tot.resid.res.} = 1\text{-}\sum_{j=1}^{m_1}\left[\left(1\text{-}k_{res,j}\right)p_j\right], \tag{4}$$

where $k_{res,j}$ is the coefficient of residual resource of PT by jth diagnostic parameter; j is number of jth diagnostic parameter; m_1 is a quantity of blocks(parameters) in parallel part of the circuit that is reduced.

The coefficient of total residual resource of PT is determined by the expression (5):

$$k_{res} = k_{wind.} \cdot k_{in.} \cdot k_{bush} \cdot k_{oil} \cdot k_{LTC} \cdot k_{cool} \cdot k_{tank}, \tag{5}$$

where k_{wind}, k_{in}, k_{bush}, k_{oil}, k_{LIC}, k_{cool}, k_{tank} are known at the moment of calculation values of the coefficient of residual resource: of the windings, of the insulation, of bushings, of the oil, of LTC, of system of the cooling, of tank of the transformer, by the elements of the transformer, correspondingly.

For the creation of mathematical model of residual resource coefficient of the transformer parameters were used, by each of these parameters the conclusion regarding the state of the transformer can be made. But none of these parameters completely characterizes technical state of the transformer, it only shows certain changes of technical state of power transformer.

Mathematical model of residual resource coefficient of the transformer was created by means of MatLab. Using this model, it is possible to edit the already created (5) probabilistic sample of teaching data. These data help to obtain analytical dependence of residual resource coefficient of the transformer on diagnostic parameters in the form of the polynomial. For seven input parameters of the model, that randomly changed from 0 to 1, the coefficient of total residual resource of the transformer (5) was determined, where input parameters of the model were reduced to relative units of their deviation from the norm.

By means of Anfis Editor using hybrid teaching algorithm and applying Sugeno algorithm of neuro-fuzzy conclusion neuro-fuzzy model of residual resource coefficient of the transformer (using subclusterization method) was obtained.

Figure 2 contains the copy of screen saver in Matlab environment where the structure of the obtained neural network is shown.

For each input variable of neuro-model four linguistic terms with Gaussian membership functions were used:

$$k_{res.i_1} = f(x_{i_1}; \sigma_{i_1}; c_{i_1}) = e^{\frac{-\left(x_{i_1}-c_{i_1}\right)^2}{2\cdot\sigma_{i_1}{}^2}}, \tag{6}$$

where δ_{i_1} and c_{i_1} are numerical parameter; $\delta_{i_1}^2$ in probability theory it is called dispersion of the distribution(14), and the second parameter c_{i_1} is mathematic expectation; i_1 is input parameter of neuro-fuzzy model, that corresponds to diagnostic parameter (i_1 = 1, 2, 3, 4, 5, 6, 7), x_i is value of i_1^{th} input parameter of the model: $x_1 - k_{wind}$, $x_2 - k_{in}$, $x_3 - k_{bush}$, $x_4 - k_{oil}$, $x_5 - k_{LTC}$, $x_6 - k_{cool}$, $x_7 - k_{tank}$.

These are such terms as: "normal" values of diagnostic parameter, "minor deviations" of diagnostic parameter value, "prefault" values of diagnostic parameter, "emergency" value of diagnostic parameter.

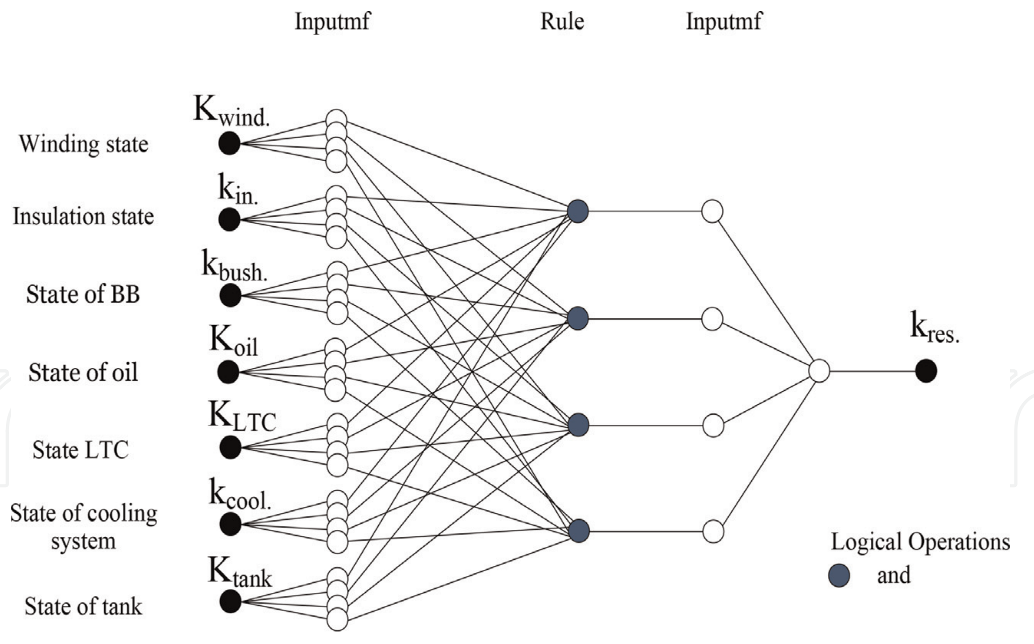

Figure 2.
Structure of Anfis-network of the transformer.

For determining the value of total residual coefficient neuro-fuzzy non-linear autoregressive model of the total residual resource coefficient of the transformer is used. This model establishes neuro-fuzzy non-linear transformation between the values of residual resource coefficients by diagnostic parameters and total residual resource coefficient of the transformer (7):

$$k_{tot.resid.res} = F(k_{wind.} \cdot k_{in.} \cdot k_{bush} \cdot k_{oil} \cdot k_{LTC} \cdot k_{cool} \cdot k_{tank}), \quad (7)$$

where F is neuro-fuzzy functional transformation.

For determination of the value of total residual resource coefficient of the transformer, we use Takagi-Sugeno model of logic conclusion.

Mathematical model of total residual resource coefficient is the system of logic equations (8).

$$\begin{cases} IF\ k_{wind.} \in "normal"\ AND\ k_{in.} \in "normal"\ AND\ k_{вush.} \in "normal" \\ AND\ k_{oil} \in "normal" AND\ k_{LTC} \in "normal"\ AND\ k_{cool.} \in "normal" \\ AND\ k_{tank} \in "normal"\ THEN \\ k_{tot.resid.res} = a_{1\ 1} \cdot k_{wind.} + a_{1\ 2} \cdot k_{in.} + a_{1\ 3} \cdot k_{bush.} + a_{1\ 4} \cdot k_{oil} + a_{1\ 5} \cdot k_{LTC} + a_{1\ 6} \cdot k_{cool.} + a_{1\ 7} \cdot k_{tank} + c_1 \\ IF\ k_{wind} \in "minordeviations\ AND\ k_{in} \in "minor\ deviation" \\ AND\ k_{вв} \in "minor\ deviation"\ AND\ k_{oil} \in "minor\ deviation" \\ AND\ k_{LTC} \in "minor\ deviation"\ AND\ k_{cool} \in "minor\ deviation" \\ AND\ k_{tank} \in "minor\ deviation"\ THEN \\ k_{tot.resid.res} = a_{2\,1} \cdot k_{wind.} + a_{2\,2} \cdot k_{in.} + a_{2\,3} \cdot k_{bush.} + a_{2\,4} \cdot k_{oil} + a_{2\,5} \cdot k_{LTC} + a_{2\,6} \cdot k_{cool.} + a_{2\,7} \cdot k_{tank} + c_2 \\ IF\ k_{wind} \in "prefault"\ AND\ k_{in} \in "prefault"\ AND\ k_{вв} \in "prefault" \\ AND\ k_{oil} \in "prefault" AND\ k_{LTC} \in "prefault"\ AND\ k_{cool} \in "prefault" \\ AND\ k_{tank} \in "prefault"\ THEN \\ k_{tot.resid.res} = a_{3\ 1} \cdot k_{wind.} + a_{3\,2} \cdot k_{in.} + a_{3\,3} \cdot k_{bush.} + a_{3\,4} \cdot k_{oil} + a_{3\,5} \cdot k_{LTC} + a_{3\,6} \cdot k_{cool.} + a_{3\,7} \cdot k_{tank} + c_3 \\ IF\ k_{wind} \in "emergency"\ AND\ k_{in} \in "emergency"\ AND\ k_{вв} \in "emergency"\ AND\ k_{oil} \in "emergency" \\ AND\ k_{LTC} \in "emergency"\ AND\ k_{cool} \in "emergency"\ AND\ k_{tank} \in "emergency"\ \ THEN \\ k_{tot.resid.res} = a_{4\ 1} \cdot k_{wind.} + a_{4\ 2} \cdot k_{in.} + a_{4\ 3} \cdot k_{bush.} + a_{4\ 4} \cdot k_{oil} + a_{4\ 5} \cdot k_{LTC} + a_{4\ 6} \cdot k_{cool.} + a_{4\ 7} \cdot k_{tank} + c_4 \\ \ldots \end{cases} \quad (8)$$

Output of the model total $k_{tot.resid.res.}$ is found as weighted sum of conclusions (8) of rules base written in the form the system of logic equations:

$$k_{tot.resid.res.} = \sum_{j2=1}^{m3} w_{j2} \begin{pmatrix} a_{j2\,1} \cdot k_{wind.} + a_{j2\,2} \cdot k_{in.} + a_{j2\,3} \cdot k_{Bush.} + a_{j2\,4} \cdot k_{oil} + \\ + a_{j2\,5} \cdot k_{LTC} + a_{j2\,6} \cdot k_{cool.} + a_{j2\,7} \cdot k_{tank} + c_{j2} \end{pmatrix}, \quad (9)$$

where $0 \le w_{j_2} \le 1$ is the degree of execution (weight) of the j_2th rule that is determined by the correspondence of real changes of diagnostic parameters of the transformer.

ANFIS is the simplest network of direct propagation that contains adaptive nodes, using the teaching rules the parameters of these nodes are arranged to minimize the error between the real output of the model $k_{tot.resid.mod.}$ and real total residual resource coefficient $k_{tot.resid.res}$ of the transformer

$$\delta = \sqrt{\frac{1}{N_1} \sum_{k_3=0}^{N_1-1} \left(k_{tot.resid.res.modk3} - k_{tot.resid.res.k3}\right)^2} \to \min, \quad (10)$$

where N is number of rows in teaching sample; k_3 is the number of the row in teaching sample, starting from the row with consecutive number "0".

Taking into account the iterative computation experiments carried out the vector of membership functions parameters is determined in **Table 2**.

Parameters	**Input parameters of the model**	**Name of the term**	**Number of the rule**	**Parameters of membership function**	
				σ	**C**
Winding state	$K_{wind.}$	Normal	1	0.3825	0.7944
		Minor deviation	2	0.479	0.5197
		Prefault	3	0.4903	0.5668
		Emergency	4	0.4	0.1697
Insulation state	$k_{in.}$	Normal	1	0.3653	0.8698
		Minor deviation	2	0.4642	0.6104
		Prefault	3	0.5102	0.5267
		Emergency	4	0.3949	0.1742
State of BB	$k_{bush.}$	Normal	1	0.3202	0.9221
		Minor deviation	2	0.3419	0.7649
		Prefault	3	0.4914	0.5376
		Emergency	4	0.4032	0.1925
State of oil	K_{oil}	Normal	1	0.4369	0.9273
		Minor deviation	2	0.3404	0.9674

Parameters	Input parameters of the model	Name of the term	Number of the rule	Parameters of membership function	
				σ	C
		Prefault	3	0.412	0.599
		Emergency	4	0.4031	0.2057
State LTC	K_{LTC}	Normal	1	0.3984	0.973
		Minor deviation	2	0.3316	0.963
		Prefault	3	0.4468	0.5881
		Emergency	4	0.4428	0.2349
State of cooling system	$k_{cool.}$	Normal	1	0.3439	1153
		Minor deviation	2	0.3507	0.9706
		Prefault	3	0.437	0.597
		Emergency	4	0.4263	0.2397
State of tank	K_{tank}	Normal	1	0.3454	0.9506
		Minor deviation	2	0.3801	1017
		Prefault	3	0.4582	0.6273
		Emergency	2	0.5451	0.564

Table 2.
Parameters of membership function.

It is seen from **Figure 2** that in the process of formation of the structure of neuro fuzzy model of the transformer seven inputs and one output of this model were set. Each of seven inputs has four terms. That is, each set of possible values of input parameters of the model is conventionally divided into four subsets: "normal" values of input parameter, "miner deviations" of the values of input parameter, and "prefault" values of input parameter, "emergency" values of input parameter. Membership degree of each value of input parameter to corresponding set of values is determined by Gaussian membership function. The model is intended for determining the numerical value of total residual resource coefficient of the transformer, that is why it has one output. This numerical value is found by means of solution of linear equation, that describes the dependence of the coefficient of total residual resource of the transformer on input parameters.

The obtained neuro-fuzzy model allows to determine the value of total residual resource coefficient of the transformer depending on the values of input parameters residual resources coefficients by each of controlled diagnostic parameters. The error of PPCT mathematical model changes from +0,004 relative units, if PPCT equals 0, to −0,032, when PPCT equals 1.

Taking into account the data of the **Table 1** and **Table 2** and (9) we obtain mathematical model of the coefficient of total residual resource in the form:

$$\begin{cases} \text{IF } k_{wind.} \in \text{"normal" AND } k_{in} \in \text{"normal" AND } k_{BB} \in \text{"normal"} \\ \text{AND } k_{oil} \in \text{"normal" AND } k_{LTC} \in \text{"normal" AND } k_{cool} \in \text{"normal"} \\ \text{AND } k_{tank} \in \text{"normal" THEN} \\ k_{tot.resid.res} = 0,6166 \cdot k_{wind} + 0,4125 \cdot k_{in} + 0,4618 \cdot k_{BB} + 1,83 \cdot k_{oil} + 1,804 \cdot k_{LTC} + \\ +0,0462 \cdot k_{cool.} + 1,96 \cdot k_{tank} - 5,377 \\ \text{IF } k_{tank} \in \text{"minor deviation" AND } k_{in.} \in \text{"minor deviation"} \\ \text{AND } k_{Bush} \in \text{"minor deviation" AND } k_{oil.} \in \text{"minor deviation"} \\ \text{AND } k_{LTC} \in \text{"minor deviation" AND } k_{cool.} \in \text{"minor deviation"} \\ \text{AND } k_{tank} \in \text{"minor deviation" THEN} \\ k_{tot.resid.res} = -0,0393 \cdot k_{wind.} + 0,2609 \times k_{in.} + 0,1086 \times k_{Bush.} - 0,37 \cdot k_{oil} - 0,1459 \cdot k_{LTC} - \\ -0,02387 \cdot k_{cool.} - 0,05863 \cdot k_{tank} + 0,1288 \\ \text{IF } k_{wind} \in \text{"prefault" AND } k_{in} \in \text{"prefault" AND } k_{Bush.} \in \text{"prefault"} \\ \text{AND } k_{oil} \in \text{"prefault" AND } k_{LTC} \in \text{"prefalt" AND } k_{cool.} \in \text{"prefault"} \\ \text{AND } k_{tank} \in \text{"prefault" THEN} \\ k_{tot.resid.res} = -0,2165 \cdot k_{wind.} - 0,3714 \cdot k_{in.} - 0,4678 \times k_{Bush.} - 0,514 \cdot k_{oil} - 0,882 \cdot k_{LTC} - \\ -0,5302 \cdot k_{cool.} - 1,406 \cdot k_{tank} + 3,88 \\ \text{IF } k_{wind.} \in \text{"emergency" AND } k_{in} \in \text{"emergency" AND } k_{BB} \in \text{"emergency" AND } k_{oil} \in \text{"emergency"} \\ \text{AND } k_{LTC} \in \text{"emergency" AND } k_{cool.} \in \text{"emergency" AND } k_{tank} \in \text{"emergency" THEN} \\ k_{tot.resid.res} = 0,03166 \cdot k_{wind.} - 0,06144 \cdot k_{in.} - 0,387 \cdot k_{Bush.} + 0,06 \cdot k_{oil} + 0,3199 \cdot k_{LTC} - \\ -0,026 \cdot k_{cool.} - 0,006 \cdot k_{tank} + 0,003 \\ \ldots \end{cases} \tag{11}$$

The obtained neuro-fuzzy model allows to determine the value of total residual resource coefficient of the transformer depending on the values of input parameters residual resources coefficients by each of controlled diagnostic parameters. The error of PPCT mathematical model changes from +0.004 relative units, if PPCT equals 0, to −0.032, when PPCT equals 1.

Despite the complexity of dependences, mathematical model of residual resource coefficient of the transformer (11) may be used for programming neuro-fuzzy controller in order to create the device for on-line determination of transformer state by means of analysis of residual resource coefficient of the transformer value.

6. Account of the forecast current value of residual resource of the transformers in the process of control of EES modes

It is known that in the process of operation, energy enterprise plans to remove out of service the equipment in the overhaul, cost of is forecast. Removal of the transformer into overhaul in a planned number of years (T_{WF}) of trouble-free operation (12 years) provides certain list of works and their expected cost $B_{oh\ pl.}$ For instance, for 330/110 kV transformers of 125–250 MVA power the cost (B) of such repair is 770–11,550 $. We propose to assume that removal out of service the transformers into current repair requires unscheduled cost.

The cost of repair may increase by the value ΔB_1, replacement of damaged blocks of the transformer and additional work, connected with the replacement. These costs are not provided in case of “typical” planned overhaul

$$\Delta B_1 = \sum_{i=1}^{n} \left(B_i \cdot e^{\gamma_i \cdot k_{res.i}^{\beta_i}} \right), \tag{12}$$

where B_i is the cost of replacement of *i*th damaged block of the transformer and additional work, connected with this replacement, n is a number of damaged blocks that require unscheduled replacement; $k_{res.i}^{\beta_i}$ is residual resource coefficient of *i*th block that requires unscheduled replacement; γ and β are coefficients, that characterize the impact of residual resource coefficient on the expected cost of unscheduled repair or replacement of *i*th block of the transformer (is determined by means of processing of statistic data).

Repair cost may increase by the cost of ΔB_2 (as compared with expected) in case of enlarged current (instead of planned overhaul) repair of the transformer, that did not operate for planned number of years:

$$\Delta B_{2_j} = \left(1\text{-}e^{\alpha_j (T_j\text{-}1)} \right) \cdot B_{OH}, \tag{13}$$

where j is a number of the transformer, T_j is time, the *i*th transformer functioned after putting into operation or after the last overhaul (enlarged current) repaint to the moment of mode control, λ is the coefficient, that characterizes the intensity of cost growth ΔB_2 that depends on the construction of the transformer, conductions and operation mode (is determined experimentally), B_{OH} is the cost of transformer overhaul.

It should be noted that removal the transformer out of service takes place not only as a result of relay protection, emergencies control automation operation but also by a person responsible for safety operation by the results of control of diagnostic parameter, values of which sometimes only approaches to limiting values.

Within the context of creation of modern Smart Grids and to provide safe, reliable, quality and economic efficient operation of EES it is necessary to perform the control over active power overflow to realize by means of the transformer, performing reliable and information archons on the mode. That is why, we suggest to take into account the coefficient of regulating transformer limitation:

$$k_{wind,j} = \left(1\text{-}k_{res,j} \right) \cdot B_{cq,j}, \tag{14}$$

where B_{cq} is the coefficient of repair cost value growth of the jth transformer.

$$B_{cq,j} = \frac{\Delta B_{1,j} + \Delta B_{2,j}}{\Delta B_{1,j} + B_{pl.,j}}. \tag{15}$$

As the example, we will consider 23 nodes 230/138 kV test circuit (**Figure 3**). In branches 11–9, 12–14, 12–9, 11–4, and 3–7 transformers ATDCTN-63000/230/138, ATDCTN-100000/230/138 and ATDCTN-125000/230/138 are installed. Initial node loads, complex transformation ratios and corresponding transformers LTC positions (number of taps) are given in **Tables 3** and **4**.

Knowing the circuit and normal node parameters we define transformation ratios.

$$k_{a.opt} = 1\text{-diag}\left(\mathrm{Re}\left(\text{-}N_{k.bal._b} \cdot Z \cdot C_e \cdot J \right) \right) \cdot U_b^{-1} \cdot E_{bal.a}^{*} \tag{16}$$

$$k_{r.opt} = \text{-diag}\left(\mathrm{Im}\left(\text{-}N_{k.bal._b} \cdot Z \cdot C_e \cdot J \right) \right) \cdot U_b^{-1} \cdot E_{bal_r}^{*} \tag{17}$$

where $N_{k.bal.b}$ is the second matrix of branches connection in contour balanced transformation ratios; Z diagonal matrix of complex branches resistances; C_e is the

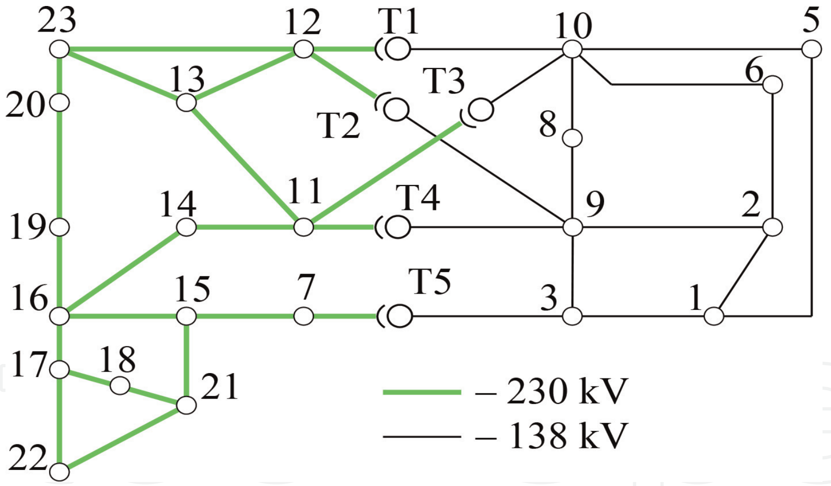

Figure 3.
Scheme of grid 230/138 kV for 23 nodes.

matrix of currents distribution coefficients for economic mode of electric network (corresponds to minimal losses of electric energy); J vector-column of currents in nodes; U_b is the voltage of basic node; $E^*_{bal.a}$ and $E^*_{bal.r}$ are balancing is electric moving in relative units (EMF) in relative units (active and reactive components).

Taking in the consideration the discrete character of LTC switching's, errors of instrument transforms, errors of data transmission channels and recommendations [20] we assume that non-sensitivity zone of active power losses may be considered as regulating actions on LTC of the transformer—to be 3% [21].

As initial conditions we assume that in accordance with load graph LTC of transformers 9–11, 9–12, 11–10, 12–10 have transformation ratios 0.6413 (14 tap), 0.6347 (14 tap), 0.6397 (14 tap), 06446 (14 tap).

It should be noted that further changes of operation mode were realized at admissible voltage deviations ±5%, from nominal voltage U_{nom}.

Regulation of the transformer 7–3 is inexpedient on conditions of the usage of the given technique of determination of transformation ratios.

We define the losses of active and reactive power in the branches of the circuit at current transformation ratios (**Table 5**).

$$\Delta S_{\Sigma\,br} = \Delta P_{\Sigma\,br} + j\Delta Q_{\Sigma\,br} = 3 \cdot \sum_{j=1}^{m} \Delta S_{br,j}, \tag{18}$$

where $\Delta S_{br} = \text{diag}\,(\Delta U_{br}) \cdot \hat{I}_{br}$ is vector-column of complete power losses in the branches of the circuit. E_{br} is vector column of the current in branches, m is a number of the branch in the circuit, $\Delta U_{br} = M_{\Sigma} \cdot U_{node}$ is vector-column of phase voltages in the nodes, ΔP_{br}, ΔQ_{br} is vector-column of active and reactive power losses in the branches of the circuit(correspondingly).

We define transformation ratios (16–17) and position of LTC on condition of minimal amount of switchings (in order to maintain switching resources of LTC) to provide minimal losses of active power in branches of the circuit of **Table 6**.

As a result of realization of control actions, mode optimization power losses were reduced from ΔS_1 = 4.49 + j29.05 (MVA) for mode (**Table 5**) to ΔS_2 = 4.42 + j28.69 (MVA). Thus, the effect of realization of transformer LTC switchings is ΔS_1-ΔS_2 = 0.07 + j0.36 (MVA). The transition from the current to mode may be performed by switching the LTC of the transformer, installed in the branch 9–12 from 13 tap to 14 and carry out transformer regulation changing position of LTC from 14 tap to 15. We will consider the transition to another stage of

Branches		R (Ohm)	X (Ohm)	k_{active}	$k_{reactive}$
№ of beginning	№ of the end				
11	10	0.6	27	0.6487	0
12	9	0.37	9.28	0.6498	0
11	9	0.3	13	0.6479	0
7	3	0.21	11.53	0.65	0
1	2	0.4951	26.471	1	0
1	3	10.398	40.221	1	0
1	5	41.516	16.092	1	0
2	4	62.464	24.129	1	0
2	6	94.649	36.565	1	0
3	9	9.882	20.962	1	0
4	9	51.038	19.749	1	0
5	10	4.342	16.816	1	0
8	9	8.82	15.124	1	0
8	10	2.067	2.145	1	0
11	23	5.207	22.793	1	0
11	14	28.566	22.112	1	0
12	23	5.207	25.18	1	0
12	13	65.596	51.101	1	0
23	13	58.719	45.759	1	0
14	16	2.645	20.578	1	0
15	16	2.338	8.404	1	0
16	17	17.457	13.701	1	0
16	19	3117	11.206	1	0
17	18	0.9522	76.176	1	0
17	22	71.415	55.704	1	0
21	22	46.023	35.866	1	0
7	15	5.68	24.865	1	0
21	18	0.873	6.851	1	0
21	15	1.666	12.96	1	0
19	20	1.349	10.474	1	0
20	13	0.741	5.713	1	0
12	10	0.31	14	0.6524	0
10	6	26.471	11.522	1	0

Table 3.
Information of circuit branches.

daily load graph(load increase), its parameters are given in **Table 7**, and optimized transformation ratios and corresponding mode parameters - in **Table 8**.

As a result of performing control actions, mode optimization we succeeded in decreasing power losses from ΔS_1 = 61.85 + j412.73 (MVA) for the mode (**Table 7**)

№ of the node	U (kV)	Phase (grad)	P_{load} (MW)	Q_{load} (MVAr)	P_{gen} (MW)	Q_{gen} (MW)
1	136.34	−5.73	108	22	182	30
2	135.54	−6.27	187.15	76	172.9	30
3	141.22	−0.94	176.4	36.26	0	0
4	136	−8.2	74	15	0	0
5	137	−8.11	68.16	13.44	0	0
6	136.36	−10.3	129.2	25.27	0	0
7	218.84	2.99	19.4	1.94	0	0
8	142.57	−7.72	169.29	34.65	131.55	131.75
9	141.55	−5.6	275	66	0	0
10	141.64	−7.29	191.1	49	0	0
11	222.36	−3.12	40	10	0	0
12	219.92	−4.12	54.88	17.64	0	0
13	236.15	7.89	0	0	495	150
14	228.34	1.56	184.3	37.05	0	101.39
15	233.22	11.21	304.32	61.44	235.2	51.32
16	233.45	10	100	20	185	80
17	237.79	15.28	35.64	13.86	0	0
18	241.5	16.92	323.01	65.96	417.1	176.19
19	231.47	7.6	177.38	36.26	0	0
20	233.81	7.31	128	26	0	0
21	241.5	17.83	0	0	425.7	146
22	241.5	25.95	0	0	420	−3.69
23	234.6	0	265	54	417.85	281.37

Table 4.
Information of the circuit nodes.

to ΔS_2 = 61.80 + j412.68 (MVA). Thus the effect of LTC transformer switchings is ΔS_1-ΔS_2 = 0.05 + j0.5 (MVA).

If as a result of determining the coefficient of regulating effect limitation for circuit transformers (**Figure 3**) the following values are obtained: $k_{wind,9–11}$ = 0.85, $k_{wind,12–9}$ = 0.4, $k_{wind,11–10}$ = 0.3 a $k_{wind,12–10}$ = 0,2, then expected quasi-decrease of losses, taking into account these coefficient will be defined.

Control actions are performed by the transformer, installed in the branch 9–11, namely, we change position of LTC with 14 tap on 15, in this case, the expected losses of active power are $\Delta P_{9–11}$ = 61.82 (MW). We find the decrease of active power losses ΔP_{Σ} - $\Delta P_{9–11}$ = 61.85–61.82 = 0.03 (MW), however, having taken into account the coefficient of regulating effect limitation, losses decrease change $\delta P_{quasi.9–11}$ = (ΔP_{Σ} - $\Delta P_{9–11}$)•$k_{wind,9–11}$ = 0.0255 (MW). New quasi-losses $\Delta P_{quasi.9–11}$ = $\Delta P_{9–11}$ + $\delta P_{quasi.9–11}$ = 61.82 + 0.0255 = 61.8455 (MW). Results of the calculation of other transformers are given in **Table 9**.

We define mode parameters for the circuit with quasi-resistances from **Table 11** and corrected transformation ratios from **Table 12**.

We find losses of active power in the branch, that contains the transformer, as function the element of vector-column of complete power losses in the branches of the circuit by the expression

P-ters*	№ of nodes																					
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
P_{load}, MW	19.44	37.43	38.8	17.02	13.63	24.55	3.49	27.08	60.5	38.22	8.4	10.43	0	29.49	39.6	20	8.55	80.75	35.47	26.88	0	0	53
Q_{load}, MVAr	3.96	15.2	7.97	3.45	2.69	4.8	0.35	5.54	14.52	9.8	2.1	3.35	0	5.93	8	4	3.33	16.49	7.25	5.46	0	0	10.8
ΔP_{Σ}, MW											4.49												
ΔQ_{Σ}, MVar											29.05												
11–10	—	—	—	—	—	—	—	—	—	0.6437		—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	—	14		—	—	—	—	—	—	—	—	—	—	—	—
12–10	—	—	—	—	—	—	—	—	—		0.6446		—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	—		14		—	—	—	—	—	—	—	—	—	—	—
9–11	—	—	—	—	—	—	—	—		0.6413		—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—		14		—	—	—	—	—	—	—	—	—	—	—	—
9–12	—	—	—	—	—	—	—	—		0.6397			—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—		13			—	—	—	—	—	—	—	—	—	—	—
9–12	—	—			0.65			—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—			14			—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

*Parameters.

Table 5.
Parameters of the current mode.

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P-ters	**№ of nodes**																						
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
$P_{load,}$ MW	19.44	37.43	38.8	17.02	13.63	24.55	3.49	27.08	60.5	38.22	8.4	10.43	0	29.49	39.6	20	8.55	80.75	35.47	26.88	0	0	53
$Q_{load,.}$ MVAr	3.96	15.2	7.97	3.45	2.69	4.8	0.35	5.54	14.52	9.8	2.1	3.35	0	5.93	8	4	3.33	16.49	7.25	5.46	0	0	10.8
$\Delta P_{\Sigma,}$. MW											4.42												
$\Delta Q_{\Sigma,}$. MVar											28.69												
11–10	—	—	—	—	—	—	—	—	—	0.6513		—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	—	14		—	—	—	—	—	—	—	—	—	—	—	—
12–10	—	—	—	—	—	—	—	—	—		0.6542		—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	—		15		—	—	—	—	—	—	—	—	—	—	—
9–11	—	—	—	—	—	—	—	—		0.6507		—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—		14		—	—	—	—	—	—	—	—	—	—	—	—
9–12	—	—	—	—	—	—	—	—		0.6521			—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—		14			—	—	—	—	—	—	—	—	—	—	—
9–12	—	—			0.65			—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—			14			—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table 6.
Transformation ratios for the current mode.

P-ters	№ of nodes																					
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
P_{load}, MW	108	187.1	176.4	74	68.16	129.2	19.4	169.2	275	39.1	40	54.88	0	184.3	304.3	100	35.64	323.0	177.3	128	0	0	265
Q_{load}, MVAr	22	76	36.26	15	13.44	25.27	1.94	34.65	66	10	10	17.64	0	37.05	61.44	20	13.86	65.96	36.26	26	0	0	54
ΔP_{Σ}, MW	61.85																						
ΔQ_{Σ}, MVar	412.73																						
11–10	—	—	—	—	—	—	—	—	—	0.6513		—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	—	14		—	—	—	—	—	—	—	—	—	—	—	—
12–10	—	—	—	—	—	—	—	—	—	0.6542			—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	—	15			—	—	—	—	—	—	—	—	—	—	—
9–11	—	—	—	—	—	—	—	—	0.6507			—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	14			—	—	—	—	—	—	—	—	—	—	—	—
9–12	—	—	—	—	—	—	—	—	0.6521				—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	14				—	—	—	—	—	—	—	—	—	—	—
9–12	—	—	0.65					—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	14					—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table 7.
Parameters of the mode after load change.

P-ters	**№ of nodes**																						
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
P_{load}, MW	108	187.1	176.4	74	68.16	129.2	19.4	169.2	275	39.1	40	54.88	0	184.3	304.3	100	35.64	323.0	177.3	128	0	0	265
Q_{load}, MVAr	22	76	36.26	15	13.44	25.27	1.94	34.65	66	10	10	17.64	0	37.05	61.44	20	13.86	65.96	36.26	26	0	0	54
ΔP_{Σ}, MW	61.80																						
ΔQ_{Σ}, MVar	412.68																						
11–10	—	—	—	—	—	—	—	—	—	0,665		—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	—	16		—	—	—	—	—	—	—	—	—	—	—	—
12–10	—	—	—	—	—	—	—	—	—	0.651			—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	—	14			—	—	—	—	—	—	—	—	—	—	—
9–11	—	—	—	—	—	—	—	—	0.6753			—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	17			—	—	—	—	—	—	—	—	—	—	—	—
9–12	—	—	—	—	—	—	—	—	0.659				—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	15				—	—	—	—	—	—	—	—	—	—	—
7–3	—	—	0.65					—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	14					—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table 8.
Parameters of mode without taking into account technical state of the transformers.

Transf.	$K_{tr.cur.}$ / $N_{cur.}$	$K_{tr.opt.}$ / $N_{opt.}$	$K_{wind. j}$	$\Delta P_{tr.j}$ (MW)	ΔP_{Σ} - $\Delta P_{tr.j}$ (MW)	$\delta P_{quasi.j}$ (MW)	$\Delta P_{quasi\ j.}$ (MW)
9–11	0.6507 / **14**	0.659 / **15**	0.85	**61.82**	0.03	0.0255	61.8455
12–9	0.6521 / **14**	0.6419 / **13**	0.46	61.83	0.02	0.0092	**61.8392**
11–10	0.6513 / **14**	0.665 / **16**	0.34	61.835	0.015	0.0051	61.8401
12–10	0.6542 / **15**	0.651 / **14**	0.25	61.84	0.01	0.0025	61.8425

Table 9.
Results of limiting effect coefficients calculation for circuit transformers.

$$\Delta P_{\alpha} = \operatorname{Re}(\Delta S_{\alpha}), \tag{19}$$

where $\Delta S_{\alpha} = \Delta U_{\alpha} \bullet I_{\alpha}$ is element of vector-column of power losses in the branches, that contain transformers, ΔU_{α} is kth element of vector-column of phase voltages drop in the branches, and I_{α} is the current of the branches with transformers couplings, α is the number of row, that correspond to the branch with transformer couplings in vector-column ΔS_{br}.

The value of quasi resistance in kth-branch:

$$Z_{\alpha} = \frac{\Delta S_{\alpha}}{\hat{I}_{\alpha}^{2}}, \tag{20}$$

where $\alpha = k + \beta$, where k – is the number of the row of the first branch, that contains the transformer, β is the coefficient of the change of consecutive number of branch, that contains the transformer, it changes in the range from 0 to$(\psi - 1)$, ψ is the number of branches, containing transformers.

Applying this algorithm, according to (20), quasi-resistances of the branches, containing transformers are found. The results of the calculations are given in **Table 10**. The aim of control is provider of minimum of all system active power losses that is determined by the expression

$$\Delta F = \sum_{i=1}^{n} \Delta P_i \rightarrow \min. \tag{21}$$

If $\Delta F_{\min.} = \Delta P_{\min.}$ is the minimum value of the efficiency function (active power losses), $\Delta F_{cur.} = \Delta P_{cur.}$ current value of efficiency function (active power

Parameters	Transformer 9–11	Transformer 12–9	Transformer 11–10	Transformer 12–10
Branch resistance, Ohm	0.3 + j13	0.37 + j9.28	0.3 + j27	0.3 + j14
Quasi resistance of the branch, Ohm	0.32 + j25.2	0.4 + j13.2	0.36 + j28.4	0.35 + j19.2

Table 10.
Quasi-resistances of transformers branches of the circuit.

P-ters	**№ of nodes**																						
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
$P_{load,}$ MW	108	187.1	176.4	74	68.16	129.2	19.4	169.2	275	39.1	40	54.88	0	184.3	304.3	100	35.64	323.0	177.3	128	0	0	265
$Q_{load,}$ MVAr	22	76	36.26	15	13.44	25.27	1.94	34.65	66	10	10	17.64	0	37.05	61.44	20	13.86	65.96	36.26	26	0	0	54
ΔP_{Σ}, MW	62.47																						
ΔQ_{Σ}, MVar	422.16																						
11–10	—	—	—	—	—	—	—	—	—	0.665		—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	—	16		—	—	—	—	—	—	—	—	—	—	—	—
12–10	—	—	—	—	—	—	—	—	—		0.651		—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	—		14		—	—	—	—	—	—	—	—	—	—	—
9–11	—	—	—	—	—	—	—	—		0.659		—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—		15		—	—	—	—	—	—	—	—	—	—	—	—
9–12	—	—	—	—	—	—	—	—			0.6419		—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—			13		—	—	—	—	—	—	—	—	—	—	—
7–3	—	—			0.65			—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—			14			—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table 11.
Parameters of normal mode after loads change, taking into account technical stale of transformers.

P-ters	№ of nodes																					
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
P_{load}, MW	108	187.1	176.4	74	68.16	129.2	19.4	169.2	275	39.1	40	54.88	0	184.3	304.3	100	35.64	323.0	177.3	128	0	0	265
Q_{load}, MVAr	22	76	36.26	15	13.44	25.27	1.94	34.65	66	10	10	17.64	0	37.05	61.44	20	13.86	65.96	36.26	26	0	0	54
ΔP_{Σ}, MW	62.46																						
ΔQ_{Σ}, MVar	422.28																						
11–10	—	—	—	—	—	—	—	—	—	0.664		—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	—	15		—	—	—	—	—	—	—	—	—	—	—	—
12–10	—	—	—	—	—	—	—	—	—	0.641			—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	—	13			—	—	—	—	—	—	—	—	—	—	—
9–11	—	—	—	—	—	—	—	—	0.6753			—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	17			—	—	—	—	—	—	—	—	—	—	—	—
9–12	—	—	—	—	—	—	—	—	0.6492				—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	—	—	—	—	—	—	14				—	—	—	—	—	—	—	—	—	—	—
7–3	—	—	0.65					—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
№ tap	—	—	14					—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table 12.
Parameters of mode after loads change, taking into account technical state of transformers and corrected transformation ratios.

losses), n is the total number of branches in the circuits, $k_{rr.min.}$ value of transformation ratio at which calculated losses of active power are minimal, then the dependence of active power losses change (values of efficiency function $\Delta F^*_{cur.} = \frac{\Delta F_{cur.}}{\Delta F_{min.}}$) in relative units on the values of transformation ratios $k* = \frac{k_{cur.}}{k_{tr.min.}}$ (**Figure 4**) for various transformers will be built.

Thus, the transition from the current to the mode can be realized by switching the LTC of the transformer, installed in the branch 9–12 from 13 tap to 14tap and perform regulation of the transformer in branch 12–10, changing LTC position from tap 14 to 15 tap are shown in **Figure 5**.

As a result of realization of control actions the mode will be reached by transformer switching of the branch 11–10 from 14 to 16 tap of LTC, transformer of the branch 12–10 from 15 tap to 14 tap, transformer of the branch 9–11 transformer from 14 to 15 tap and transformer of the branch 9–12 from 14 to 13 tap of LTC, respectively, how are shown in **Figure 6**.

We see that due to consideration of technical state of transformers, their ranking occurred by the measure of impact on the reduction of active power losses. To reach mode now it is more expedient to use a transformer of 9–12 branch as it during one switching of LTC from 14 tap to 15 tap reduces most active power losses.

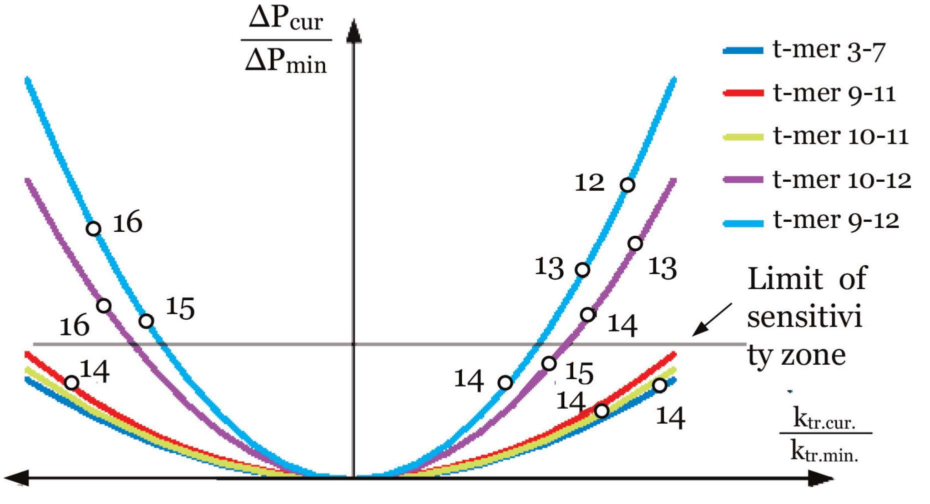

Figure 4.
Charts of dependencies of changes in active power loss on the values of transformation ratios for small loads mode.

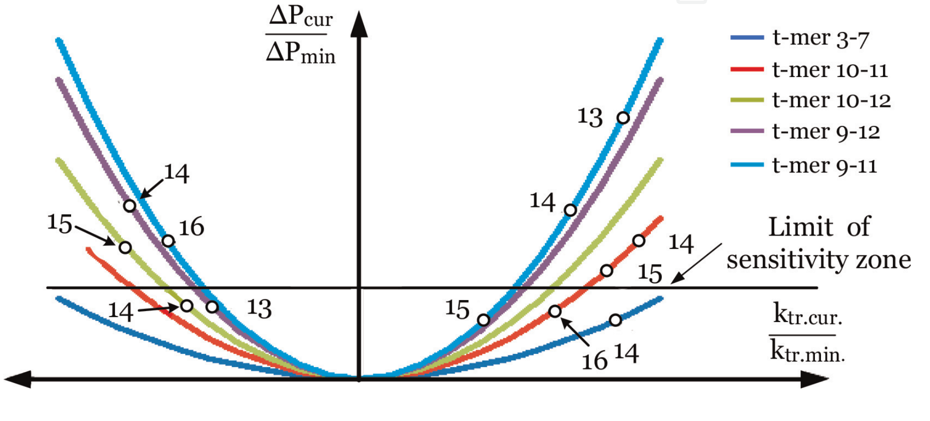

Figure 5.
Charts of dependencies of changes in active power loss on the values of transformation ratios for large loads mode, without taking into account technical state of the transformers.

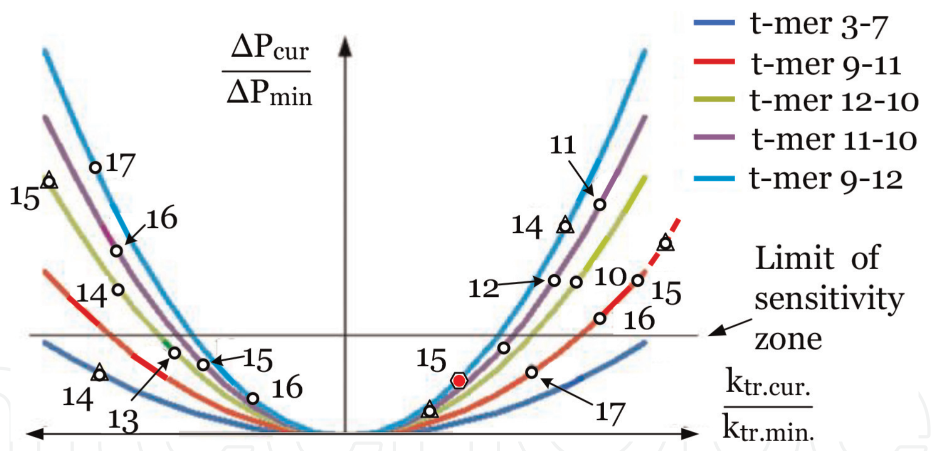

Figure 6.
Transformation ratio for large loads mode, taking into account technical state of the transformers.

7. Discussion of the results of transformation ratios of EES transformers determination, taking into account the state of transformers

The analysis of the articles showed that neuro-fuzzy logic methods are used to solve various problems of operating electric power systems, such as improving power quality [18], classifying the faults of the electrical equipment based on sequence components [19], developing of the controller of the tariff, which based on neuro-fuzzy logic for the for distributing active power between a micro network and EPC for improving energy quality [20].

The error of RRCT determination by means of the developed mathematical neuro-fuzzy model, as compared with teaching sample and to the opinion of independent experts does not exceed the error of the devices, measuring diagnostic parameters. Such results are explained by complex usage of probability theory methods neuro-fuzzy modeling and modern software Matlab. These results also confirm the information provided in the article by Moudud Ahmed, Naruttam Kumar Roy. In their article [21], it is written that the use of automatic systems for adaptive control of electric power systems (EPS) based on neuro-fuzzy modeling and based on an inference system (ANFIS) is promising method. This improves EPS performance, for example, reduces power losses. Similar positive results of using neuro-fuzzy logic are described in the article by Priyanka Ray and A.K. Sinha [22]. This article says that the use of neuro-fuzzy logic has allowed the development of a hybrid control system that provides the maximum generated electrical power of hydro, wind and solar power plants even under incomplete data on current weather conditions and power consumption.

Also, in the works [23–25] of the authors H. Suna, R. M. Velasquez; J.W.M. Lara; Dong Ling; Yao-Yu Xu; Yu Liang; Yuan Li; Ning Liuand Quan and Jun Zhang were reviewed methods of intelligent diagnostics of transformers that use fuzzy logic and in the future can be applied to improve diagnostic systems and other power equipment.

Such feature of the suggested method for determining the control actions of LTC-transformers, as account of PPCT, in the process of ES modes control, provides such advantages as reduction of the equipment damage rate, decrease of active power losses in the EPS. Due to the of the peculiarities method of determination of control action of LTC-transformers, taking into account their technical state, perspectives of developments and introduction in EPS of modern microprocessor –based systems, automatic control of LTC of transformers become possible.

As compared with the known method of voltage drop control on the branches of EPS circuits, with the method of overloads decrease of transmission lines, at the expense of redistribution of power overflows in EPS, decrease of active power losses in the process of transportation by means of LTC- transformers, the suggested method allows to select, by means of account the suggested RRCT, the transformer for EPS mode control, that would simultaneously provide the reduction of power losses and is more reliable.

Usage of quasi-resistances of circuit branches, that unlike the transformers used, in the process of calculation of nominal resistances of the branches, take into account transformers state and possible losses of utility companies due to possible damages, allows to calculate EPS mode in rise of transformers transformation ratio change and by means comparison of calculated power losses select the most efficient transformer.

The suggested peculiarity of application the method of neuro-fuzzy modeling (usage in teaching sample the model of transformer resource instead of measured values of diagnostic parameters - calculated and partially corrected by independent experts of coefficients of residual resource) enables to take into account simultaneous impact on RRCT the results of both current and periodic control.

The drawback of the suggested mathematical neuro-fuzzy model of RRCT is necessity of large data base regarding coefficient of residual resource of diagnostic parameters CRRDP (Coefficient of residual resource of the diagnostic parameter) for specific transformers. Attempt to reduce database or use the model from other similar transformer results in the increase of model error. Limitation on the usage of RRCT model is the necessity of application only on one – investigated transformer. Therefore, we need models for each transformer. The method of determination of control actions by LTC transformers does not take into account voltage limitations in nodes and current limitations in the branches of the circuit.

Further development of the given research will be realized in the development of mathematical models of other types of high voltage equipment, involved in the process of EPS modes control, damage of which areas place (**Figure 7**).

Problems of the considered research development are caused by the necessity of long lasting experiments and observations over the processes of aging and development of high voltage equipment damage, processes of EPS modes parameters change not only on computer ad mathematical models of the equipment and EPS modes and on real equipment.

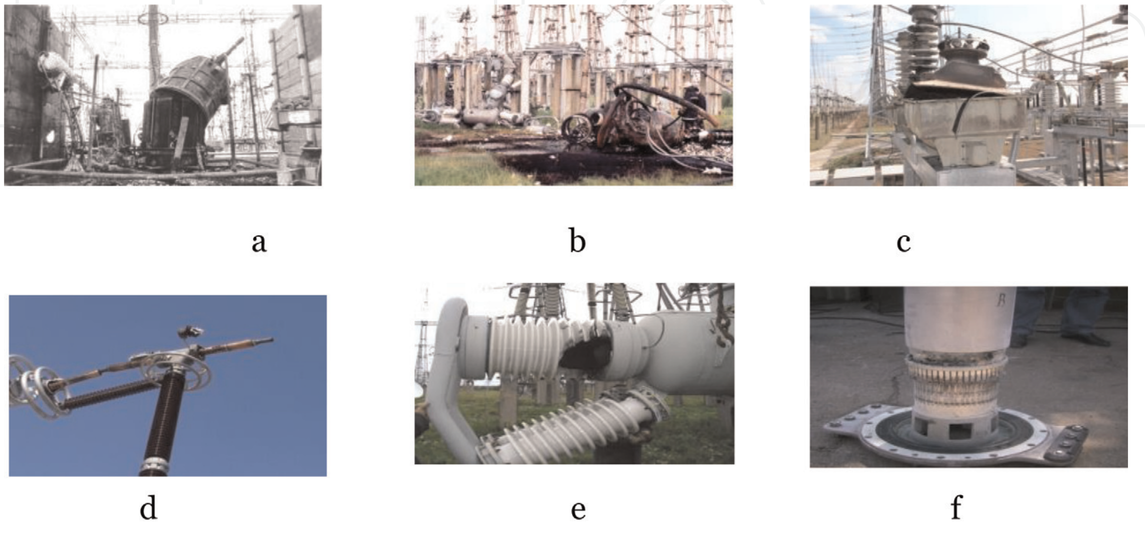

Figure 7.
Damage of high voltage equipment in EPS: (a) 750 kV shunt reactor; (b) current transformer and 750 kV air circuit breaker; (c) 33 kV voltage transformer; (d) 750 kV SF_6 circuit breaker; (e) air circuit breaker; (f) 110 kV SF_6 circuit breaker.

8. Conclusions

1. Analysis of damager ate of power transformers and methods of the EPS modes control allows to state that it is a necessary to use the results of on-line diagnostics of LTC-transformers not only to determine the expediency of further operation or repair of the equipment and for calculation transformation values (with the account of the suggested RRCT) for their usage in the process of modes control.

2. The model enables, by means of accounting, of both current and retrospective values of diagnostic parameters on RRCT and determine its current value. That is necessary for automatic and automated reliable and control of EPS modes.

3. Improved method of determination of control actions by LTC- transformers, by means of comparative analysis of the results of EES modes with quasi resistances of circuit branches, enables to soled the transformer and calculate transformation ratio that provides minimal amount of LTC switching.

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