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EVALUATION AND INCREASE OF LOAD CAPACITY OF ON-LOAD TAP CHANGING TRANSFORMERS FOR IMPROVEMENT OF THEIR REGULATING POSSIBILITIES

Розроблена математична модель прогнозованої температури верхніх шарів оливи трансформатора з врахуванням залишкового ресурсу охолоджувачів. Для оцінювання технічного стану системи охолодження трансформаторів і визначення їх реальної навантажувальної здатності використовується нейро-нечітке моделювання. Показано, що максимальне використання навантажувальної здатності трансформаторів дозволяє покращити їх регулювальні можливості і використати їх для підвищення ефективності оптимального керування режимами електроенергетичних систем

Ключові слова: силовий трансформатор, навантажувальна здатність, математична модель,оптимальне керування, зона нечутливості

Разработана математическая модель прогнозируемой температуры верхних слоев масла трансформатора с учетом остаточного ресурса охладителей. Для оценки технического состояния системы охлаждения трансформаторов и определения их реальной нагрузочной возможности используется нейро-нечеткое моделирование. Показано, что максимальное использование нагрузочной способности трансформаторов позволяет улучшить их регулирующие возможности и использовать их для повышения эффективности оптимального управления режимами электроэнергетических систем

Ключевые слова: силовой трансформатор, нагрузочная способность математическая модель, оптимальное управление, зона нечувствительности

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1. Introduction

It is well known, that due to non uniformity of electric networks their power is naturally distributed in such a way, that imbalance currents emerge in the network, and, as a result, additional losses of power and electric energy [1, 2]. Negative impact of electric network non uniformity can be compensated, changing their parameters or introducing EMF, by which balancing reverse currents are induced. Balancing EMF in the contours of electric networks are introduced by means of special booster transformers (BT) or by selection of transformation ratios of the transformers by which electric networks of different voltages are interconnected.

Among measures, aimed at reduction of electric energy losses, usage of the transformers for power flows correction in electric networks is recommended as the most efficient means of energy losses reduction during its transmission [3, 4]. The efficiency of this method considerably increases when the process of power flows optimal control is carried out in automatic mode. For this purpose automatic regulators and systems of automatic control of transformation ratios of the transformers with on load tap changing have been developed.

However, electric energy losses reduction using optimal control of power flows in electric networks will become efficient only when technical states of the transformers and autotransformers, involved in the process of control must be satisfactory and their residual resource and current loading capacity must have certain reserve. For their determination it is necessary to create corresponding methods and means of on-line diagnostics of the transformers and autotransformers. It is obvious that they must use the possibility of modern hardware and software and be based on SMART GRID principles.

Nowadays the change of energy branch structure that existed for many years and transition to another level of functioning, connected with intelectualization of electric energy systems (EES) is taking place [5–9]. However, along with the intensive development of EES infrastructure and introduction of SMART GRID technologies certain discrepancy, caused by functional unpreparedness of power equipment (for instance, power transformers) to radical changes in EES is observed. The process of optimal control of EES modes is complicated and the efficiency of control impacts is reduced due to the fact that the portion of the equipment, that used up normative term or is close to depletion of its technical resource is constantly growing [10, 11].

The aim of the paper is the development of the method for determination of current loading capacity of transformers and auto transformers with on-load tap changing and ways of its increase, improving their cooling system.

2. Analysis of literary sources and problem set-up

One of the problems, efficient solution of which must provide necessary condition for quality functioning of EES in modern conditions is the improvement of the flows of active and reactive power. Such system must provide the control of transit and auxiliary transfers of power on condition of minimum losses of electric energy in electric networks. Main facilities of such control are power transformers and auto transformers with longitudinally-transversal regulation and linear regulators of various constructions and operation principles.

In [12] it is suggested to use the statements of the theory of control and monitoring of discrete-occurrence systems for the solution of the problems of control in energy systems, for instance, voltage control problems by means of on-load tap-changing of the transformer location change but technical state of these transformers is not taken into account, that under certain conditions may lead to their damage.

In [13] two algorithms, regarding optimal location of on-load tap-changing transformers in electric energy systems by the criterion of minimal losses of energy in them, are suggested.

However, as in [12] current loading capacity of the transformers with on-load tap-changing at the moment of realization of control impact, recommended in [13], is not taken into account. In [14] various technologies, techniques and on-line approaches are considered aimed at: efficient improvement of the systems of transmission and distribution of electric energy; at the accuracy of evaluation and reduction of technical and nontechnical losses of electric power and energy. For instance, it is suggested to: introduce smart networks, evaluate the state of distribution , use automatic devices of control impacts supply on the equipment of electric energy systems (on-load tap-changing transformers , electric high voltage switchers, etc.) Smart Grid concept provides the usage of on-line system of technical state monitoring of the equipment, but in [14] it is not shown, how to determine current state of cooling system of the transformer and how it can be taken into account for determination of current loading capacity of the transformers for efficient and reliable control of EES modes.

In [15] it is noted that nowadays, according to the strategy of energy development for perspective, distinct trends of rapid growth of power of reconstructed and introduction of new generating sources are revealed. This circumstance determines urgent need of active construction and modernization of high voltage equipment of electric networks. In [15] the attention is paid to the problems of longitudinal and transversal regulation of power flows distribution in phases, however, considering technical difficulties of efficient development of combined devices, intended for control of electric energy systems modes with simultaneous longitudinal and transversal regulation of electric power flow distribution, maintaining the possibilities of their individual regulations in EES, methods and means of determination and account of current loading capacity of the transformers are not suggested in the paper, that shows the necessity of further studies, aimed at the increase of operation reliability and efficiency of transformers with on-load tap-changing control, taking into account their current loading capacity.

As there exist certain problems, dealing with renovation of the transformers and autotransformers, able to participate in the control of power transfers in EES and promote the introduction of new technologies in EES, then we should try to find new ways, alternative to replacement of old transformers by new ones. In such condition, the analysis of transformers and autotransformers loading in electric networks is very actual [16]. By the results of such analysis, it is known, that for the part of power transformers, it is expedient and technically possible to increase loading capacity and use them more intensively in optimal control [17]. For this purpose it is necessary to use the results of on-line diagnostics of the transformers and autotransformers and improve their cooling system. The first will enable to evaluate their real technical state and possibilities regarding the participation in optimal control, and the second measure will increase their loading capacity and broaden their control possibilities.

To evaluate real control possibilities of the transformers it is necessary to define their real loading. This is performed by means of measurement of electric loading on the day, when daily schedules of active and reactive electric loading are set. However, taking into account great number of consumers and transformer substations, expenses for measurements - both of time and material resources, considerably exceed the value of the information, obtained by direct measurement of the information, regarding the load. At the same time, in many cases, maximum loading of transformer substations can be determined with rather high accuracy by means of calculation and on the base of the results of measurements, according to recommendations [16]. Knowing the forecast value of transformers loading and their technical state we can predict the temperature of the upper layers of oil and limitations on loading capacity of the transformers.

The problem of on-line diagnostics of transformers state in the process of optimal control of EES normal modes , taking into account technical state of their cooling system, current and forecast loading according by the place of operation, arises. Determining factor in the suggested approach is research and taking into account, by means by mathematical modeling, individual peculiarities both of the transformer and its operation conditions in retrospective and perspective, that can be generalized in the form of characteristic indices. As this task, by its nature is partly fuzzy and indefinite, then corresponding method of mathematical modeling is required.

3. Purpose and objectives of the study

The aim of the research is the creation of technique, intended for evaluation and increase of loading capacity of the transformers and autotransformers to use them more efficiently in optimal control of power flows in electric energy systems.

To reach the suggested aim the following tasks were put forward:

1. Develop mathematical model for evaluation of technical state of cooling system of transformers and autotransformers, adequate to information support and necessary accuracy of power flows optimal control in electric energy systems.
2. Develop the algorithm of neuro-fuzzy modeling and determination of transformers and autotransformers real loading capacity, taking into account residual resource of coolers, using the forecast temperature of upper layers of oil as an integral index.
3. Develop the method of usage of additional possibilities of the transformers, obtained as a result of the increase of their loading capacity in automatic system of power flows control in electric energy systems.

4. Nero-fuzzy model of the resource coefficient of the transformer on-load tap changing, taking into consideration the state of cooling system

During operation the state of cooling system becomes worse, that leads to temperature growth of the upper layers of oil and influences the loading capacity of the transformer. Knowing the forecast schedule of loading we must provide possible pre- emergency or emergency temperature growth of the upper layers of oil and we should take measures, aimed at coolers cleaning, and in case of necessity, repair of oil pumps, fans, systems of fans and oil pumps control, change of seals, etc. Fig. 1 shows typical damages of transformer cooling system.

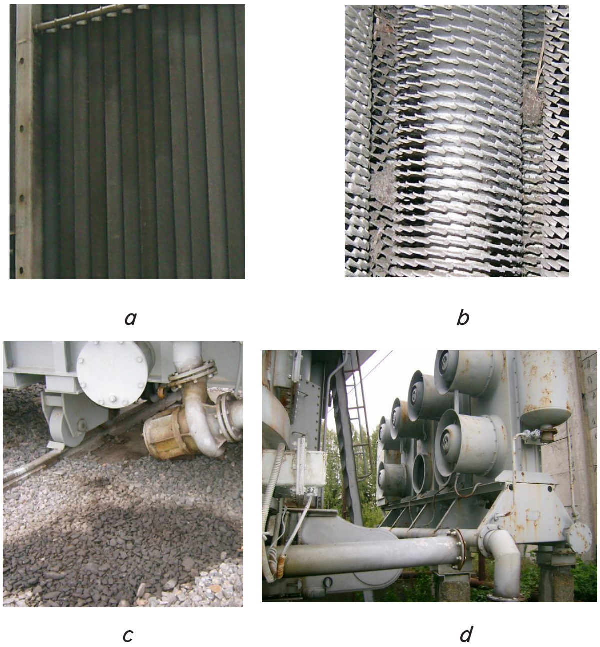
a b c d

Fig. 1. Damages of autotransformer cooling system: *a* — leakage of the oil from the pipes of the cooler, that worsens cooling abilities of the cooler; *b* — adherence of the grass, leaves, mass, that worsens convective heat transfer from the surface of the cooler; *c* — leakage of the oil as a result of the damage of oil pump seal, its electric motor and filter; *d* — damage of electric motor of the fan, installed at one of the coolers

Fig. 2 shows the diagram of evaluation of controlled parameters influence on residual resource of the cooling system. The diagram takes into consideration the coefficient of residual resource of oil pumps, fans and coolers; $K_{op1}\div K_{op8}$ – coefficient of total residual resource of oil pumps (if, for instance, there are eight such oil pumps, then K_{op} coefficients will be eight); $K_{fan1}\div K_{fan16}$ – coefficient of total residual resource of the fans (if, there are 16 such fans, then K_{fan} coefficients will be also 16); $K_{col1}\div K_{col8}$ – coefficient of total residual resource of the coolers (if, there are eight such coolers , then K_{col} coefficient will be eight); $K_{col,1}$ – coefficient of total residual resource of the first cooling module, consisting of the cooler, oil pump, two fans (if, for instance, there are eight coolers, then cooling modules will be eight).

The coefficient of residual resource of oil pump is determined by the coefficients of residual resource by the parameters: temperature of frontal surfaces of stator winding, stator current, service life of electric motor, pressure of oil after oil pump and vibration (vibrating speed) of its body. The coefficient of residual resource of the fan is determined by the coefficients of residual resource by the parameters: temperature of frontal surfaces of stator winding, stator current, service life of electric motor.

The coefficient of residual resource of the cooler is determined by the coefficient of residual resource by the parameter of temperature difference between input and output of the oil in the cooler, taking into account the temperature of upper layers of the oil in the transformer tank, loading of the transformer and air temperature.

In order to obtain generalized index of residual resource of the cooling module and then the system of transformer cooling that takes into account the values of all diagnostic parameters and their impact, it is suggested to pass from known values of all diagnostic parameters (in denominated unit) to the coefficient of residual resources, that correspond to these values, by each diagnostic parameter. These coefficients are determined in relative units and characterize total operation of cooling module from the moment of its technical state control to transition into boundary state, when diagnostic parameter reaches limiting value, i. e., residual technical resource:

$$k_i = \left|\frac{x_{i,lim}-x_{i,cur}}{x_{i,lim}-x_{i,in}}\right|, \qquad (1)$$

where $x_{i,lim}$ – limiting normative value of the ith diagnostic parameter, $x_{i,lim}$ – value of ith diagnostic parameter at the moment of control, $x_{i.in}$ – initial value of ith diagnostic parameter (at the moment of putting into operation new transformer or after repair).

For oil pump of the autotransformer АТДЦТН 200000/330/110 parameter P (oil pressure after the pump) after repair equaled 1,5 kg/cm^2 (at operating oil pump), and at the moment of control equaled 1,1 kg/cm^2 , limiting value of this parameter – 0,9 kg/cm^2. That is why, the coefficient of residual resource K_r by diagnostic parameter P is determined by the expression:

$$k_P = \left|\frac{1.5-1.1}{1.5-0.8}\right| = 0.57\,(\text{r.u.}).$$

According to Fig. 2. the scheme is reduced by the following expressions. For serial part of the scheme, the coefficient of total residual resource is found by the expression:

$$k_{res}=\prod_{i=1}^{\nu}k_i^{p_i}, \qquad (2)$$

where k_i – coefficient of residual resource of cooling module by i^{th} diagnostic parameter, ν – number of blocks in the serial part of the scheme, p_i– probability of controlled parameter deviation from limiting admissible normalized value of this parameter.

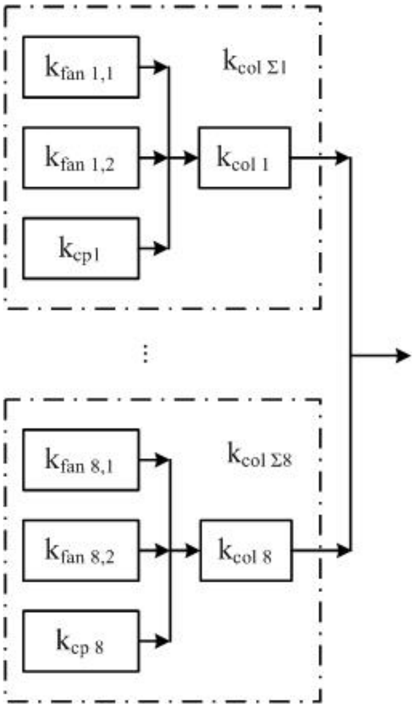

Fig. 2. Diagram of controlled parameters impact on the resource of transformer cooling system

For parallel part of the scheme coefficient of total residual resource is found by the expression:

$$k_{res\Sigma}=1-\sum_{j=1}^{m1}\left[\left(1-k_{res,j}\right)p_j\right], \qquad (3)$$

where k_j – coefficient of residual resource of cooling system by j^{th} diagnostic parameter, m_1 –number of blocks in parallel part of the scheme, being reduced.

In order to simplify the calculations and lack of sufficient number of the results of diagnostic parameters control (for instance, probability of damaging of oil pumps of electric motors, revealed by means of control of stator winding current exceed over its normalized value) simplified technique of determination of total residual resource of cooling system can be used. Instead the coefficient of residual resource of each cooling module it is suggested to use general coefficient of residual resource of all cooling modules [18]. If we assume, that worsening of the state of one cooler does not influence the state of the other, then total coefficient of residual resource is determined.

$$k_{res.tot.,j}=\sum_{i=1}^{n}\lambda\cdot k_{res.i,j}, \qquad (4)$$

where $\lambda=1/8=0{,}125$ – coefficient, that takes into account the impact of each cooler, taken separately.

As an example, we will analyze statistical data of nine years survey of the parameters АОДЦТН 330000/250/330 transformer for determination of the temperature of upper layers of oil, depending on the active power load (P_{ld}), time of load (T), temperature difference between input and output of the cooler (Δt), air temperature (T_{air}). It is suggested, instead of temperature difference between input and output of i^{th} cooler to take into account its coefficient of residual resource (k_{res}), that changes in the process of operation from 1 to 0 and is determined by the expression:

$$k_{res.\ i,,j}=\Delta t_{cur.\ i,j}/\Delta t_{op.\ i,,j}, \qquad (5)$$

where Δt_{cur} – current value of temperature difference for j^{th} mode, $\Delta t_{op.\ j}$ – value of temperature difference of operational transformer for j^{th} mode.

Fragment of observation results is presented in table 1 (complete sample contains 2457 observations). In the process of observations and analysis of the results (table 1) of observation regarding the impact of coolers state on the temperature of upper layer of oil auto regressive model NARX (Nonlinear Autoregressive Exogenous Model) with external input is used. It establishes fuzzy transformations between previous changeable values of such argument as averaged loading of the transformer P_{ld} during time T, air temperature t_{air}, coefficient of residual resource of cooler $R_{res.}$ (7) and forecast value, also changeable in the process of operation ($t_{up\ lay}$) of the function f(P_{ld}, T, t_{air}, $K_{res.}$).In the investigated auto transformer cooling system contains eight coolers, eight oil pumps (six operational and two additional that start operating, when transformer load exceeds 75 % of the nominal and 16 fans – four fans per each cooler).

In the process of operation there is a possibility to control the temperature of upper layer of the oil ($t_{up\ lay}$) by means of standard thermometer or other thermometer, the result of measurements will be showed on microcontroller of the system of constant control and from the controller – to automatic working place of the dispatcher of the substation.

Table 1

Result of the observations over the change of upper layer of oil temperatures

P_{ld}, MW	T, hours	t_{air},°C	Δt_{cur},°C	Δt_{op},°C	K_{res}, r.u.	$t_{up\ lay}$,°C
121	4	13	7,67	8,67	0,89	52
85	4	15	7,14	7,14	1	42
...	...	...	...	...	...	...
125	4	17	9,69	9,69	1	57
...	...	...	...	...	...	...
143	4	24	7,2	10,2	0,71	63
...	...	...	...	...	...	...
210	4	32	7,6	11,6	0,66	72
...	...	...	...	...	...	...
140	4	36	3,9	10,9	0,36	71
...	...	...	...	...	...	...

To obtain the dependence

$$t_{up\ lay}=f(P_{ld}, T, t_{air.\ i}, k_{res}), \tag{6}$$

mathematic apparatus of fuzzy modeling is used.

For determination of the forecast value of upper layer of oil temperature Sougeno model of logic conclusion is used. For this model of aggregation operation of the membership function of output variable $t_{up\ lay}$ and transformation of the fuzzy set into definite number (defuzzification) is replaced by the operation of weighted addition of rules conclusion [19]. Reference of the rules are presented by linguistic variables, described by fuzzy terms. For input variable P_{ld} – transformer loading this is: term – "small" loading (less than 40 % from the nominal), term – "average" loading (from 40 % to 75 %) and "large" (more than 75 %). For input variable T- time is: term "small" (less than 0,1 hour), term – "average" (from 0,1 to 1 hour), "large" (more than 1 hour). For input variable t_{air} – temperature of air is: term – low (less than –5 °C), term – close to zero (from –5 °C to +5 °C) and term – large (more than +5 °C). For input variable – coefficient of residual resource (k_{res}) is: term – small (less than 0,3 r.u.), term – average (from 0,3 r.u. to 0,6 r.u.) and term – large (more than 0,6 r.u.)

Base of fuzzy rules of cooling system – these are rules that enable to determine forecast value of the temperature of upper layer of oil, depending on the power of daily schedule stage of transformer loading, duration of this stage, air temperature and coefficient of residual resource of cooler. NARX model of the cooler contains base of 72 rules. Fragment of rules base has the following form:

…

IF $P_{ld\ (k-1)}$ is "average" AND T_{k-1} is "small" $t_{air\ (k-1)}$ is "high" AND $k_{res\ (k-1)}$ is "small"

THEN $t_{up\ lay\ (k-1)}=\sum_{i=1}^{n} a_{(k-1),i}\cdot\prod_{j=1}^{m} x_{(k-1),i,j}^{\alpha_{(k-1),i,j}}+c_{k-1}$;

IF $P_{ld\ (k)}$ is "average" AND T_k is "large" $t_{air\ (k)}$ is "high" AND $k_{res\ (k)}$ is "small" THEN $t_{up\ lay\ (k)}=\sum_{i=1}^{n} a_{(k),i}\cdot\prod_{j=1}^{m} x_{(k),i,j}^{\alpha_{(k),i,j}}+c_k$;

IF $P_{ld\ (k+1)}$ is "average" AND T_{k+1} is "small" $t_{air\ (k+1)}$ is "large" AND $k_{res\ (k+1)}$ is "small"

THEN $t_{up\ lay\ (k+1)}=\sum_{i=1}^{n} a_{(k+1),i}\cdot\prod_{j=1}^{m} x_{(k+1),i,j}^{\alpha_{(k+1),i,j}}+c_{k+1}\prod_{j=1}^{m} x_{(k+1),j}^{0}$;

…

where k-1, k, k+1 – numbers of rules that correspond to the state of cooling system of the transformer; i=number of item in polynomial equation; j – number of multiplier in the product of argument for each of the items of polynomial equation; a – coefficient before each of products, c – absolute term of polynomial equation; α – degree of each of the arguments, x – arguments ($x_1= P_{ld}$, $x_2= T$, $x_3= t_{airi}$, $x_4= k_{res}$)

$$t_{uplay,\,k}=\sum_{k=1}^{72} w_k\cdot\left(\sum_{i=1}^{n} a_{k,i}\cdot\prod_{j=1}^{m} x_{k,i,j}^{\acute{a}_{k,i,j}}+c_k\prod_{j=1}^{m} x_{k,j}^{0}\right), \tag{7}$$

where $0\le w_k\le 1$ normalized to one the weight of each kth rule on which correspondence of calculated forecast value of the temperature of upper later of oil depends to real by the same values of P_{ld}, T, t_{air}, k_{res}

$$w_k = \\ =\frac{\mu_{k,\text{"average"}}(P_k)\cdot\mu_{k,\text{"}large\text{"}}(T_k)\cdot\mu_{k,\text{"high"}}(t_{air,\,k})\cdot\mu_{k,\text{"small"}}(k_{res,\,k})}{\sum_{g=1}^{72}\mu_g(P_g)\cdot\mu_g(T_g)\cdot\mu_g(t_{air,\,g})\cdot\mu_g(k_{res,\,g})}, \tag{8}$$

where $\mu_k(P_k)$, $\mu_k(T_k)$, $\mu_k(t_{пов})$, $\mu_k(k_{res})$ values of membership function of input parameters to corresponding (by the conditions of the rules) sets; $P_k\in P_{\text{"average"}}$ i $T_k\in T_{\text{"large"}}$ i $t_k\in t_{\text{"high"}}$ i $k_k\in k_{\text{"small"}}$, because if one of these conditions is not satisfied, then corresponding (for instance kth) rule will not be taken into account in the conclusion (in general conclusion) of the model; g – number of the rule, for instance g=k.

Total non-optimized quantity of rules – 72.

Terms, corresponding to linguistic variable are set in the form of Gauss membership functions.

During training, according to the date from the journals of long-term observations the parameters of rules conclusions have been obtained, fragment of these conclusion is given below:

…

IF "loading"="average" AND "time"="average" AND "air temperature"="large" and "coefficient of residual resource"=small THEN "temperature of upper layer"$-33{,}8\cdot P\cdot k_{res}+0{,}1646\cdot t_{air}\cdot k_{res}+4{,}5381\cdot k_{res}^2-0{,}8\cdot k_{res}-$ $-0{,}013\cdot P\cdot t_{air}+0{,}008\cdot t_{air}^2-0{,}078\cdot t_{air}+1{,}083\cdot P+\ldots$;

IF "loading"="average" AND "time"="large" AND "air temperature"="large" and "coefficient of residual resource"=small THEN "temperature of upper layer"$=-29{,}8\cdot P\cdot k_{res}+0{,}11\cdot t_{air}\cdot k_{res}+2{,}81\cdot k_{res}^2-0{,}4.k_{res}-$ $-0{,}0198\cdot P\cdot t_{air}+0{,}007\cdot t_{air}^2-0{,}06\cdot t_{air}+1{,}24\cdot P+\ldots$;

IF "loading"="average" AND "time"="small" AND "air temperature"="large" and "coefficient of residual resource"=small THEN "temperature of upper layer"$=-42{,}5\cdot P\cdot k_{res}+0{,}121\cdot t_{пов}\cdot k_{res}+2{,}963\cdot k_{res}^2-14{,}93\cdot k_{res}-$ $-0{,}0123\cdot P\cdot t_{air}+0{,}0046\cdot t_{air}^2-0{,}0924\cdot t_{air}+0{,}976\cdot P\ldots.$

As an example the case is considered when for single phase autotransformer of АОДЦТН 333000/750/330 type in accordance with daily load schedule it is planned to increase the loading capacity up to P=214 MWA and maintain such power during three hours (T=3) and at this time the temperature of the air t_{air}=30 °C and pollution of cooler surfaces corresponds of the coefficient of residual resource of the cooler k_{res}=0.355 r.u. the forecast temperature of upper layer of oil will be $t_{up\ lay}$=80 % that exceeds maximum normative value of 75 % and will require loading decrease in order to decrease the temperature. That is why, it is necessary to clean the cooler. After cleaning k_{res}=1 r.u. Then at P_{ld}=214 MWA, T=3 hours, t_{air}=30 °C – temperature of upper layer of oil will be $t_{up\ lay}$=65 %. At the same conditions there is a possibility to increase the transformer loading by 36 % i. e. up to 333 MWA (nominal loading). In this case, the temperature increases only to $t_{up\ lay}$=70 % that does not exceed normative values.

In other conditions for instance, if T=8 hours k_{res}=0.355, P_{ld}=220 MWA, t_{air}=32 %, then $t_{up\ lay}$=74 % and if k_{res} increase to 1 r.u. the temperature decrease to $t_{up\ lay}$=59 % and this enables to increase loading up to 333 MWA ($t_{up\ lay}$=71 %), namely by 34 %.

If T=0,5 hours $k_{res}=0.355$, $P_{ld}=270$ MWA, $t_{air}=36$ %, then $t_{up\ lay}=74$ % and at $k_{res}=1-t_{up\ lay}=41$ % that enables to increase loading up to 333 MWA (by 19 %), at $t_{up\ lay}=47$ %.

5. Impact of transformers capacity on the optimality zone of EES modes

Modern systems of automated and automatic control have errors of the sensors and measuring channels, errors of optimality criterion definition that can be stipulated by the imperfection of the model or inaccuracy of the method and calculation algorithm. Total errors can reach 5 % and more [20]. In order to provide efficient usage of the transformer with on-load tap changing resource the composition of the transformers, participating in the realization of control actions is optimized.

For these transformers corresponding transformation ratios and their influence on optimality criterion is evaluated.

By the results of such analysis of sensitivity of optimality criterion setting parameters of local systems of automatic control (ACS) – set points and non-sensitivity zones of ACS are determined [21].

Fig. 3 shows how the increase of loading capacity of the transformers, involved in optimal control of power flows in EES can improve the quality of control and reduce electric energy losses in the process of its transformation.

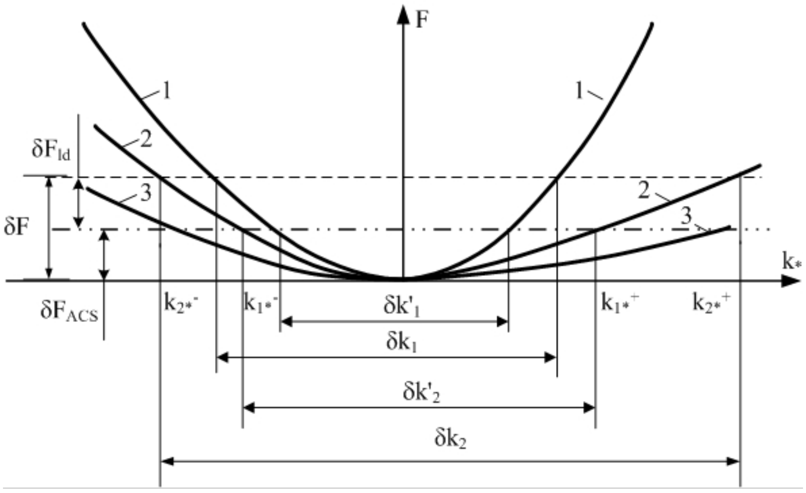

Fig. 3. Dependences of optimality criterion on the change of transformation ratios of the transformers with on-load tap changing, taking into account their loading capacity

In order that non-sensitivity zone of ACS by the transformers be not less than their regulation stage, optimality zone of optimality operation F must be not less than δF_{ACS}. In reality, taking into account unsatisfactory state of transformers and their insufficient resource, optimality zone δF is established. Non-sensitivity zones of transformation ratios of the transformers δk_1, and δk_2, correspond to it. For the third transformer, non-sensitivity zone exceeds its regulating range, i. e., it is not used in the process of optimization of power flows.

If loading capacity of the transformers is increased, as it is shown in the example, considered above, then optimality zone δF can be reduced by δF_{ld}, even to δF_{ACS}. In such case, non-sensitivity zones of the transformers transformation ratios decreased to $\delta k_1'$, and δk_2. As a result, admissible number of switches of on-load tap changing will grow and, correspondingly , the possibility of the transformers to influence power transfers will grow.

That is, in practice, admissible optimality zone δF of optimality criterion F to the change of transformation ratios must be determined by two components, that are formed, depending on two reasons. The first reason – it is a necessity to create normal conditions for ACS operation, and the second reason – admissible loading of the transformer, by means of which control actions are realized:

$$\delta F = \delta F_{ACS} + \delta F_{ld}. \qquad (9)$$

The first component is relatively constant by value. It is stipulated by errors of telemeasurements and on-load tap changing parameters of the transformers. The second component depends on loading capacity of the transformers with on-load top changing, also depending or technical state of transformers cooling system. In the process of operation in must be recalculated.

6. Conclusions

1. Real loading capacity of the transformers and autotransformers depends on their technical state and numerous external factors (load schedules, ambient temperature, operation conditions, etc.) To use efficiently transformers and autotransformers with on-load tap changing in optimal control of power flows in EES in order to decrease electric energy losses in the process of its transmission, it is necessary to know their current loading capacity.

2. Loading capacity of the transformers and autotransformers depends on the technical state of their cooling system, technical state of the system can change greatly in the process of operation. Mathematical model of the forecast temperature of upper levels of oil has been developed, the given model, among other parameters, takes into consideration the residual resource of the coolers. For evaluation of technical state of transformers cooling system, means of neuro-fuzzy modeling are used, as a result, functional connections between influencing factors are taken into account. For determination of the forecast value of the temperature Sugeno logic conclusion model is used.

3. Neuro-fuzzy model of loading capacity of the transformer, depending on its resource coefficient has been developed.

Admissible loading of the transformer is determined, depending on its resource coefficient, air temperature, time, loading and is limited by maximally admissible temperature of upper layers of oil.

4. It is shown that maximum usage of loading capacity of the transformer, if it makes part of automated control system of EES mode, is rather simply realized by means of the mechanism of establishment of corresponding non-sensitivity zone of on-load top changing operation. In order to provide economic usage of the transformer resource the

selection of the transformers, participating in realization of control impact is optimized, by means of determination of corresponding transformation ratios and their influence on optimality criterion. Coordination of transformers operation in the system of power flows in EES optimal control is realized by setting parameters of non-sensitivity zones of ARS, that are determined, taking into account loading capacity of transformers.

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