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OPTIMAL CONTROL OF ELECTRIC ENERGY SYSTEMS NORMAL MODES, TAKING INTO ACCOUNT TECHNICAL STATE OF ON-LOAD TAP-CHANGING TRANSFORMERS

Method of determination of control impacts of-load tap-changing transformers has been improved, taking into account quality factor of their functioning. Its application enables to evaluate the expedience of performing control impacts and reduce expenditures, caused by transformers faults. For determination of quality factor of on-load tap-changing transformers it is suggested to take into account technical state of cooling system.

Key word: *cooling system, power transformer, optimal control, normal modes, electric energy system.*

Introduction

Characteristic feature of modern electric energy system (EES), that complicates the control process and substantially reduces the efficiency of control impacts, is the growth of the share of the equipment, that completed its useful life period. In case of necessity to prolong operation period of the equipment, there appears the problem of current state of the equipment and resource balance determination. In many countries of the world, including Ukraine, the share of equipment, that completed its service life, exceeded half of the total volume [1, 2]. That is why, present stage of energy branch development imposes higher demands regarding trouble free operation of such equipment. It is specified by the decrease of the rate of new equipment development, growth of energy objects capacities, competition among utility companies, caused by transition to energy market.

Correspondence between current and optimal values of optimality criterion(power losses) in EES is achieved at the expense of intensification of regulating devices RD) operation. This leads to additional reduction of their technical resource, decrease of operation reliability, that, in its turn, results in failures and losses, sometimes proportional and even greater than technical-economic effect, achieved as a result of optimization. That is why, it is necessary to develop mathematical models, intended for optimal control of electric energy system (EES) normal modes (NM) taking into account technical state of regulating devices (RD). This enables to use more efficiently on-load tap-changing transformers to reduce electric energy losses in the process of its transportation.

Hence, taking into account the above- mentioned, the aim of the research is to reduce power losses in electric energy systems as a result of improvement of normal modes parameters control, considering regulating ability of on-load tap-changing transformers and their technical state.

Material and results of the research. Operating staff, forming the control impacts, takes into account technical state of the equipment. The choice of the transformer, to be used for optimal control of EES normal modes (NM), is carried out, taking into consideration the following reasons: switching should be performed by the most reliable transformer, because failure of the transformer while switching leads to expenses for repair, which may exceed the losses as a result of system operation in non-optimal mode if non-reliable transformer is not used; usage for NM parameters control the transformer, which is in better technical state, as compared with other transformers, to provide their optimal values does not always provide optimal operation mode, because this transformer may be insensitive to maintain the mode at the given moment of time; calculated number of switchings to maintain optimal mode (some transformers may be referred to the category of the equipment with emergency low residual resource, and for other transformers only insignificantly reduces their resource).

That is why, it is suggested to use the coefficient of operation quality as the criterion of transformer choice, which better performs switchings and chooses the amount of switchings. Operation quality coefficient takes into account reliability characteristics of the transformer (in particular, residual resource), transformer loading and sensitivity of power losses changes in EES to switchings of on load regulator of this transformer. Switching is to be performed by the transformer, where operation factor is the highest [2]. It is very complicated to choose the corresponding transformer, taking into account the fact, that it is necessary to minimize losses and provide the reliable operation of on-load regulator (OLR) (reduce the number of failures in on-load regulator).

Let us consider the problem of determining quality coefficient of transformer operation, depending on its impact on losses in energy system and its residual resource.

Quality coefficient of transformer operation is a complex parameter, that takes into consideration not only the ability of the transformer to convert electric energy, but also the possibility to influence efficiently the mode of energy system [3 – 4], and is determined by the expression:

$$k_{q.f.} = (a_1 + a_2) \cdot k_{sw.r.} \cdot k_{c.r.} \cdot k_{res\,I} \cdot a_3 \cdot k_{loss} \quad (1)$$

where k_{loss} – is coefficient of active power losses during transmission of electric energy in transmission lines; $k_{res.\,sw.}$ – is the coefficient of transformer residual resource by the parameter of switchings quantity by on load regulator (OLR); a_1, a_2, a_3 – are weight coefficients, $k_{res.I}$ – is residual recourse coefficient by the parameter "switching current accumulated by "regulating device", residual resource coefficient ($k_{c.\,res.}$) of the transformer cooling system.

Losses coefficient is calculated by the expression (2):

$$k_{loss} = \frac{\Delta P_{nopt} - \Delta P_{opt}}{\Delta P_{nopt}}, \quad (2)$$

where $\Delta P\ opt$ – is optimal value of active power losses for current mode of EES; ΔP_{nopt} – is the value of active power losses if the transformer is not used for switching.

Residual resource coefficient by the parameter "accumulated switching current" is determined by the formula (3),

$$k_{res\ I} = \frac{I_{ac.r.} - \sum_{m=1}^{n} I_{com.m}}{I_{\lim.ac}}, \quad (3)$$

where $I_{ac.r.}$ – a residue of switching current, accumulated OLR, is determined by the formula (4):

$$I_{ac.res.} = I_{\lim.} - I_{ac.cur.}, \quad (4)$$

where $I_{sw.\ m}$ – is the current across OLR during m^{-th} switching, m –is a number of switching, n – is amount of switchings, needed for obtaining of optimal mode, $I_{lim.res.}$ – is limiting value of switching current, accumulated by RUL. (to be taken from technical documentation for OLR).

Coefficient of residual resource is determined by the parameter of switchings number by the formula (5):

$$k_{sw.res,\,i} = \frac{n_{res.i-1} - n_i}{n_{\lim.}}, \quad (5)$$

where $n_{res.\ i-1}$ – is residual number of OLR switchings after i-1^{-th} series of switchings, determined by the expression (6)

$$n_{res.i-1} = n_{lim.} - n_{till}, \quad (6)$$

where $n_{lim.}$ – is limiting number of switchings by OLR, (to be taken from technical documentation for RUL), n_{till} – is the member of switchings, performed by OLR till i-1^{-th} series of switchings; n_i – is a number of switchings during the i^{-th} series of switchings.

Weight coefficients are determined by the expressions (7 – 9):

$$a_1 = \frac{B_1}{B_{int.}}, \tag{7}$$

$$a_2 = \frac{B_2}{B_{int.}}, \tag{8}$$

$$a_3 = \frac{B_3}{B_{int.}}, \tag{9}$$

where B_1, B_2 – cost of electric energy lost as a result of operation by repair scheme and cost of transformer OLR reparation in case of its damage during switchings.

Cost of over normative technical power losses is determined by the expression (10):

$$B_3 = \left(\Delta P_{cur} - \Delta P_{norm}\right)\cdot \tau \cdot C , \tag{10}$$

where ΔP_{cur} – is current value of active power losses; C – is the price of 1 кW/·h of electric energy, transmitted in the networks of EES; τ – is duration of the period between switchings, hours; ΔP_{norm} – is normative-value of technical losses of active power.

Integrated cost of electric energy (B_{int}) is determined by the expression (11):

$$B_{int} = B_1 + B_2 + B_3 . \tag{11}$$

Coefficient of residual resource ($k_{res.cool\ j,i}$) of one j^{-th} cooler, that changes in the process of operation from 1 to 0 r.u. for one cooler is determined by the expression (12):

$$k_{res.cool\ j,i} = \frac{\Delta t_{cur\ j,i}}{\Delta t_{op.\ j,i}}, \tag{12}$$

where i – is the number of load mode (i^{-th} series of OLR switchings.), $k_{res.\ cool.\ j,i}$ depends on the temperature differences of transformer oil before and after cooler, $\Delta t_{cur\ j,i}$ – is current value of the temperature differences for i^{-th} mode of j^{-th} cooler, $\Delta t_{op.\ j,i}$ – is the value of the temperature differences of operational transformer for i^{-th} mode of j^{-th} cooler.

Total coefficient of residual resource of all coolers, calculated by the expression (13) is used:

$$k_{res.cool.} = \sum_{i=1}^{n} \lambda \cdot k_{res\,i,j} , \tag{13}$$

where $\lambda = 1/\Omega$ – is the coefficient, that takes into account the impact of each cooler on the coefficient of total residual resource of cooling system; Ω – is the number of coolers (worsening of technical state of one cooler does not influence the state of another cooler).

Further, regulating signal on OLR of transformers is formed, it is proportional to the deviation of current integral power losses in electric energy system from their optimal values, the formed signal is matched with the signal, that takes into account limitations: by voltage; frequency; maximum allowable current of transmission lines; non-sensitivity zone of regulator under voltage, by normalized system-wide losses of electric power in transmission lines; by the results of matching, if it is necessary, previously formed regulating signal is corrected, after words this signal is sent to OLR drive of the transformer [5]. Fig. 1 shows functional diagram of automatic system of electric energy system mode regulation [6].

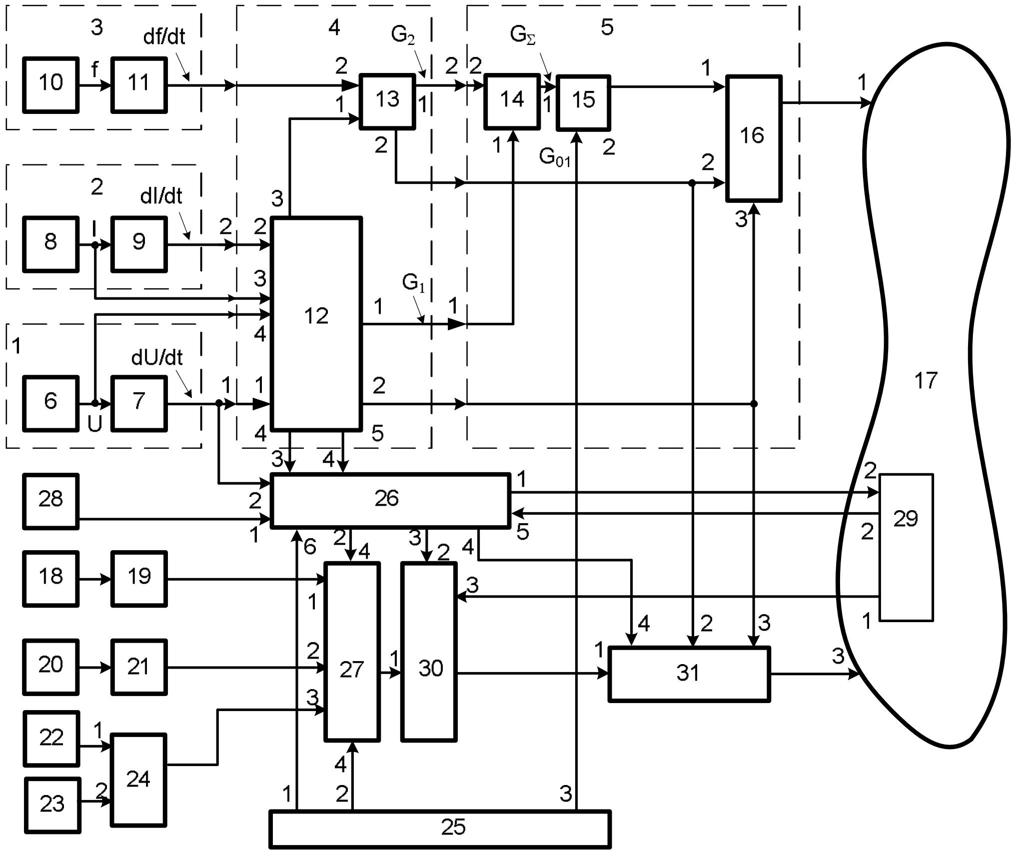

Fig. 1. Diagram of automatic system of optimal control of EES NM parameters

Operation algorithm of optimal control system of EES NM, considering technical state of transformer cooling system

In the process of voltage deviation rate definition in the unit of voltage deviation rate definition 1, the signal from measuring unit 6 is sent to differential unit 7, output signal of which is proportional to voltage change rate in controlled nodes of the system. To define current deviation rate in the unit of current deviation rate 2, signal from measuring unit of current 8 arrives to differential unit of current 9, output signal of which is proportional to current change rate in controlled sections of the system.

Rate of frequency deviation (in the unit of frequency deviation rate 3 is determined, taking into account the signal, that arrives from measuring unit of frequency 10 to differential unit of frequency 11, output signal of which is proportional to frequency change rate in the system. Output signals from differential unit of voltage 7 and differential unit of current 9 are sent, correspondingly, to the first and second outputs of unit 4, intended for determination of sensitivity of electric network mode to external disturbances, where at the first output of the first computational unit 12 output signal, proportional to losses, resulted from deviation of power transfers along controlled sections from their optimal values is formed. In the first computational unit 12 power change rate in transmission lines is calculated, power transfers in each of the lines is defined, also power of node loading, partial derivative $\left[\dfrac{dU}{dS}\right]$, that corresponds to voltage dependence on the change of node power are determined. These parameters are used for the output signal formation, proportional to losses, resulted from power transfers deviations along controlled sections from their optimal values.

At the second output of the first computational unit 12, the signal of power excess, which is transmitted along transmission lines over maximum allowable values, is formed. At the third output of the first computational unit 12 signal, proportional to the node load change rate is formed.

Signals from the output of differential frequency unit 11 of the unit 3, intended for definition of frequency deviation rate and signal from the third output of the first computational unit 12, arrive, correspondingly, on the second and first inputs of the second computational unit 13, where frequency change rate in the system $\frac{df}{dS}$ is determined and deviation of current frequency value from nominal frequency value are compared.

At the first output of the second computational unit 13 signal, proportional to economic losses, resulted from frequency deviation value is formed, whereas at the second output signal, indicating the presence of frequency value deviation from maximum value of such deviation, is formed.

In the adder 14 of unit 5, designed for formation of signals of electric energy system operation mode control, signal from the first output of the first computational unit 12 is added to the signal from the first output of the second computational unit 13, which arrive, correspondingly, on the first and second inputs of adder 14. Signal from the first output of the first computational unit 12 is proportional to the losses, resulted from deviations of power transfers along controlled sections. Signal from the first output of the second computational unit 13 is proportional to economic losses, resulted from deviation of frequency value from maximum allowable value of such deviation.

Signal (G) from the output of adder 14 is sent to the first input of comparison unit 15, where it is compared with signal (G_0), proportional to the value of economically substantiated losses, which is regulation setting. Signal G_0 arrives at the second input of comparison unit 15 from PC in the course of periodic programming of comparison unit 15 and is stored in the memory of comparison unit 15. If $G \geq G_0$, signal from the output of comparison unit 15 is sent to the first input of control unit 16. At the third input of control unit 16, the signal, indicating the excess of power from the second output of the first computation unit 12 is sent, the signal indicating the deviation of frequency value from maximum value of such deviation from the second output of the second computation unit 13 is sent to the second input of control unit 16. Taking into account the signals at the inputs of control unit 16 the signal is formed at its output.

From the output of control unit 16, signal in the form of regulating impacts is sent to the first input of electric energy system 17, namely, at the actuators of electric energy system 17 (for instance, drives of high voltage switches), responsible for operation mode and EES structure change, for instance, by means of reserve line connection.

By means of accumulated current sensor 18 of electric motor, current of electric motor of RUL drive is measured (measure immediately after termination of starting current flow, on condition, that stable mode current does not exceed the error of its control).

Coefficient of residual resource is determined by the parameter of ”accumulated switching current” of RUL drive and, in this way, control if the current of the motor does not exceed the set value.

For this purpose, at the input of the third computational unit 19, where values of residual resource coefficient are calculated by the parameter «accumulated switching current», of RUL drive, signal arrives from the output of current sensor 18 of electric motor, installed in control unit of RUL.

From the output of the third computational unit 19 signal, proportional to the coefficient of residual resource by the parameter «accumulated switching current», is sent to the first input of the seventh computational unit 27, where values of OLR operation quality factor are calculated.

The coefficient of residual resource by the parameter «accumulated switching current» is calculated by the formula (3).

The coefficient of residual resource by the parameter «number of switchings» is determined in the fourth computational unit 21. Number of OLR switchings for each transformer is calculated by means of switch number sensor of RUL 20, installed in RUL control unit. The coefficient of residual resource by the parameter «number of switchings» is determined for each transformer. For this purpose at the input of the fourth computational unit 21 signal from the output of OLR number of switchings sensor 20 is sent. From the output of the fourth computational unit 21, signal, proportional to the coefficient of residual resource by the parameter «number of switchings», is sent to the second input of the seventh computational unit 27.

The coefficient of residual by the parameter «number of swiching» is calculated by the formula (5).

The coefficient of residual resource by the parameter «temperature difference between input and output of the cooler» is determined in the fifth computational unit 24. For this purpose, the signal from the output of temperature sensor at cooler input 22 is sent to the input of the fifth computational unit 24; at the second input of the fifth computational unit 24 the signal is sent from the output of temperature sensor at cooler output 23. The coefficient of residual resource by the parameter «temperature difference of transformer oil before and after cooler» is calculated by the formula (12).

In the sixth computation unit 26 of RUL switching influence, system- wide power losses in transmission lines, optimal quantity of switchings, coefficient of OLR switching influence by controlled z^{-th} transformer (where z – is the number of the transformer) on the system-wide losses of power, considering the limitations, are calculated: by voltages in the nodes, by currents in brunches, by extreme positions of RUL and by non-sensitivity zone of OLR. Limitations are set and corrected in the sixth computation unit 26 by means of the signal, sent from the first output of portable computer 25 at the sixth input of the fifth computation unit 26.

Signal from measuring voltage unit 6 and signal from measuring current unit 8 are sent, correspondingly on the third and fourth inputs of the first unit. From the fourth and fifth outputs of unit 12 signals are sent on the third and fourth inputs of the sixth computation unit 26 of OLR switchings impacts. From the second output of this unit signal, proportional to the coefficient of RUL switching impact of controlled transformer is sent to the fifth input of the seventh computation unit 27 of operation quality coefficient. The signal from the fourth output of unit 12 is proportional to the load of substation. The signal from the fifth output of unit 12 is proportional to the power, transmitted in transmission lines of the substation.

Signal from the output of OLR drive position sensor 28, that corresponds to the number of regulation stage is sent to the first input of the sixth computation unit of RUL switching impact 26. Signal from the output of measuring voltage unit 6 is sent to second input of the sixth computation unit 26 of RUL switchings impact. Signal from the second output of on-line information complex of electric energy system 29 is sent to the fifth input of the sixth computation unit 26 of RUL switchings impact. This signal contains information regarding powers in branches and nodes of electric energy system circuit. The signal from the first output of the sixth computation unit 26 is sent to the second input of on-line information complex 29 of electric energy system 17. This signal contains information regarding loads of controlled substation branches. The coefficient of z^{-th} transformer RUL impact on system-wide losses ($k_{imp.\ m,i}$) is determined by the expression:

$$k_{imp.m,i} = \frac{\Delta P_{non-used,i} - \Delta P_{opt.,i}}{\Delta P_{non-used,i}},$$

where $\Delta P_{\text{non-used, i}}$ – are system wide losses of power in transmission lines as a result of non-usage of RUL switching of z^{-th} transformer, $\Delta P_{\text{opt., i}}$ – are system wide losses of power in transmission lines as a result of usage of z^{-th} transformer RUL in order to determine optimal position of OLR taking into account limitations by voltage in nodes, by currents in branches and by extreme positions of RUL.

From the output of the third computation unit 19 the signal is sent to the first input of the seventh computation unit 27, where value of coefficient of transformer operation quality is determined.

From the output of the fourth computational unit 21 the signal is sent to the second input of the seventh computational unit 27 where the value of transformer operation quality coefficient is determined.

From the output of the fifth computational unit 24 the signal is sent to the second input of the seventh computational unit, where the value of transformer operation quality coefficient is determined.

From the second output of the sixth computational unit 26 the signal is sent to the fifth input of the seventh computational unit 27. This signal contains information regarding the value of impact coefficient of RUL switching by controlled $z^{\text{-th}}$ transformer on system wide power losses.

The coefficient of transformer operation quality is determined taking into account the coefficient of RUL residual resource by the parameter «accumulated switching current », the coefficient of residual resource of RUL by the parameter « number of switchings», the coefficient of OLR residual resource by the parameter ”temperatures difference between input and output of the cooler”, the coefficient of RUL switching impact by $z^{\text{-th}}$ transformer on system wide power losses, cost of lost electric energy as a result of operation by repair scheme, cost of OLR transformer repair in case of its damage during switchings, cost of additional technical losses of power.

Information, regarding the cost of lost electric energy as a result of operation by repair scheme, cost of RUL transformer repair in case of its damage during switchings, cost of additional technical losses of power is sent from the second output of portable PC on the fourth input of the seventh computational unit 27.

From the first output of on-line information complex of electric energy system 29 the signal concerning active power change in nodes is sent to eighth computational unit 30.

The signal from computational unit 30 is sent to the first input of unit 31. Transformer, which is used to perform correcting impact by greater value of operation quality coefficient is determined. For this purpose, the signal from the fourth output of the sixth computational unit 26 is sent to the fourth input of transformer choice unit 31 of automatic system of normal modes parameters control of electric energy system. The signal from the first output of on-line information complex 29 of electric energy system 17 arrives at the third input of transformer choice unit 30. This signal contains information regarding the coefficients of operation quality of other transformers of electric energy system. Ranking of transformers according to the values of operation quality coefficients is performed in transformer choice unit 30.

By the results of ranking the transformer with greater value of operation quality coefficient is chosen.

Regulating signal on OLR of the chosen transformer is formed proportionally to the deviation of current losses of power in EES from their optimal values, taking into account the value of transformer operation quality for current mode; signal of available exceeding of power, that is transmitted along transmission lines, over maximum allowable value of power of these lines. For this purpose, the signal from the output of transformer choice unit 30 is sent to the first input of signal conditioner on RUL transformer 31, from the output of which signal is sent to the third input of electric energy system 17, namely, at OLR drive of the chosen transformer of electric energy system 17.

At the fourth input of signal conditioner on OLR transformer 31, the signal concerning the number of OLR switchings of chosen transformer is sent from the fourth output of sixth computational unit 26 and signals from other outputs are sent on the second and third inputs of signal conditioner on OLR transformer 29: correspondingly of the first computational unit 12 and second computational unit 13. These signals block signal formation at the output of signal conditioner on OLR transformer 31 in emergency mode of electric energy system operation.

Conclusions

Improvement of the method of control impacts by on-load tap-changing transformers on EES normal modes is expedient to perform, taking into account technical state of cooling system, that enables to improve the quality of operation and reliability of these transformers .

REFERENCES

1. Кириленко О. В. Інформатизація та інтелектуалізація систем керування в електроенергетиці: деякі

підсумки за останні роки / О. В. Кириленко, А. В. Праховник // Технічна електродинаміка: спеціальний випуск. – 2010. – С. 10 – 17.

2. Алексеев Б. А. Контроль состояния (диагностика) крупных силовых трансформаторов / Б. А. Алексеев. – М.: Изд-во НЦ ЭНАС, 2002. – 216 с.

3. Рубаненко О. Є. Контроль та покращення навантажувальної здатності трансформатора / О. Є. Рубаненко, О. І. Казьмирук // Вісник Вінницького політехнічного інституту. – 2011. – № 6 – С. 63 – 68.

4. Лежнюк П. Д. Оперативне діагностування трансформаторів в задачах оптимального керування / П. Д. Лежнюк, О. О. Рубаненко // Вісник Хмельницького національного технічного університету. – 2007. – № 2. – С. 185 – 189.

5. Лежнюк П. Д. Оптимальне керування нормальними режимами електроенергетичних систем критеріальним методом з урахуванням планового значення технічних втрат потужності / П. Д. Лежнюк, О. О. Рубаненко // Вісник Вінницького політехнічного інституту. – 2011. – № 1. – С. 86 – 90.

6. Пат. 61058 Україна, МПК[8] H O2 J 3/24. Спосіб оптимального керування нормальними режимами електроенергетичної системи / П. Д. Лежнюк, О. О. Рубаненко; заявник і патентоутримувач Вінницький національний технічний університет. – № u201014272. – заявл. 29.11.10 ; опубл. 11.07.11. Бюл. № 13, 2011 р.

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