P. D. Lezhnyuk, Dr. Sc. (Eng.), Prof.; Jean-Pierre Ngoma, Cand. Sc. (Eng.), Assist. Prof.; A. V. Kylymchyk

AUTOMATION OF POWER FLUXES CONTROL IN ELECTRIC ENERGY SYSTEMS BY MEANS OF CROSS-TRANSFORMERS AND OPTIMUM MODES SIMILARITY

The paper considers the problem transversal-longtitudinal regulation of power fluxes and voltage in electric networks using cross-transformers and autotransformers as the problem of automatic control, the aim of it is formation of optimum control law and creation of corresponding system of automatic control. The given problem is solved on the basis of EES modes similarity and using criterial modes similarity and using criterial relations between their parameters.

Key words: *transversal-longtitudinal control, power fluxes, cross-transformers, autotransformer, similarity.*

Introduction

Considering complex natures of electric energy system (EES) as the object of control and specific character of its operation mode, it becomes quite obvious that only systems of automatic control (SAC) enable to monitor and modify optimum values of parameters relatively EES states, applying corresponding regulation facilities.

Cross – transformer technologies, widely used by Federal Control System (FCS) of Russian Federation could be used as regulation devices. These devices have a number of advantages as compared with existing ones [1]. The given paper, on the basis of regularities, established in [2, 3] considers the functioning of ACS by power fluxes and voltage within the system of optimum control of normal modes (NM) of EES with simulation model [4]. In the given paper the problem of EES modes optimization is put forward as the problem of automatic control, the aim of its solution is formation of optimal control law by power fluxes, including transit, and creation of corresponding automatic control system (ACS) .

Power fluxes control in EES

Electric networks of energy- supplying companies function parallely, that is why variations in operation mode of one network influence the state of others (Fig 1). That is, mutual influence of electric networks is observed. The result of non – optimality of such influence is additional losses of electric energy, which reduce economic efficiency of energy supply companies. The volume of additional losses depends on the degree of inhomogeneity of electric networks of high voltage (HV) and low voltage (LV). Main and least expensive method of inhomogeneity reduction is application of existing regulating transformers and coupling autotransformers (CAT). Due to various values of coupling autotransformers transformation ratios certain comparison current I_{cc}, appears in the networks, which compensates non – balance current I_{nb} , resulted from inhomogeneity of EES. In real EES a number of problems are stipulated by application of coupling autotransformers. Some of these problems are: non – sufficient regulation range, needed for compensation of negative influence of inhomogeneity and nonsatisfactory technical state of RUL devices.

In other words, by means of autotransformers with RUL we can only partially compensate EES inhomogeneity. The task is considerably worsened in case, when EES performes transit of electric energy. In this case proper fluxes are overlapped by transit ones, which must be controlled in order to reduce losses in EES.

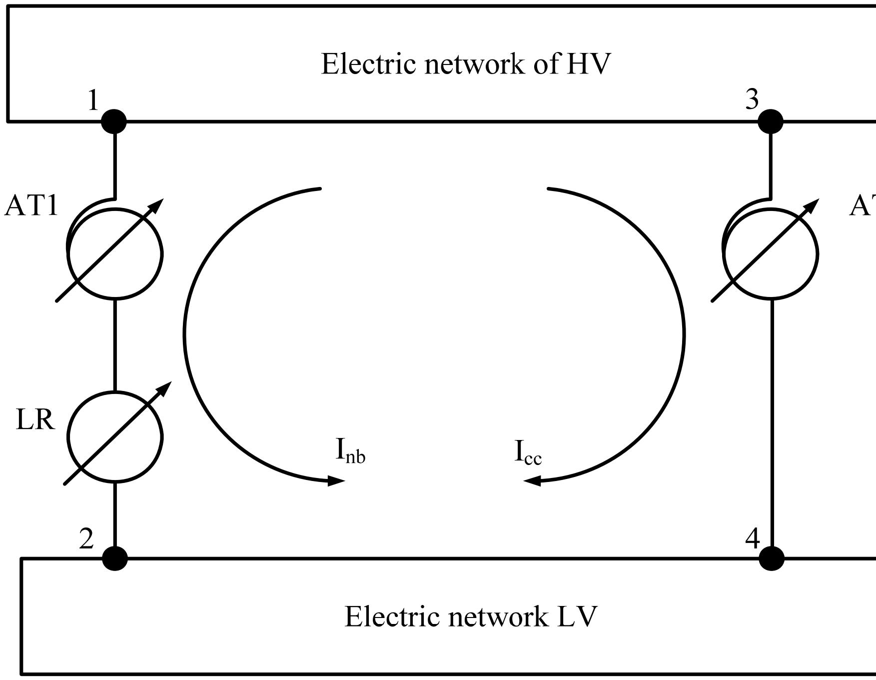

Fig. 1. Structural diagram of parallely operated electric networks

For expansion of regulating ability of AT it is recommended to install linear regulator (LR) in series with AT. Cross – transformers (CT) in the system of power fluxes regulation perform the function of regulators, which optimize relatively stable, deep non – balance fluxes. AT with RUL are used for compensation of relatively small disturbance in EES, caused by voltage variations of energy consumers load and generation at electric power stations. Thus, the problem of coordination of CT and AT with URL appears.

Operation of ACS, considered in the paper, of EES coupling transformers, which connect electric networks of different voltages in a single electric system, is aimed at reduction of energy losses while its transmission in EES by means of redistribution of natural power fluxes and their forced approach to flux distribution in uniform EES. This task can be referred to the class of problems of dynamic systems control theory with square – law criterion of optimality (for instance, active power losses):

minimize

$$F(u) = \int_{t_0}^{t_k} \left[x_t(t) Q x(t) + u_t(t) R u(t) \right] dt \qquad (1)$$

in states space

$$\left. \begin{aligned} &\frac{dx}{dt} = Ax(t) + Bu(t); \quad x(t_o) = x_o; \\ &y(t) = Cx(t) + Du(t), \end{aligned} \right\} \qquad (2)$$

where, u(t), y(t) – are vectors of state, control and monitoring, correspondingly; A, B, C, D, Q, R – are matrices of constant coefficients; t_o, t_k – are start and end of time interval; x_o – initial value of state vector.

In the given model

$$u(t)=\begin{bmatrix}\dot{k}_{at}(t)\\ \dot{k}_{ct}(t)\\ Q(t)\end{bmatrix};\quad y(t)=\begin{bmatrix}\dot{S}_{в}(t)\\ \dot{I}_{в}(t)\\ \dot{U}(t)\end{bmatrix}, \tag{3}$$

where $\dot{k}_{am}(t)$, $\dot{k}_{\kappa m}(t)$ – are vectors of complex transformation ratios of AT and CT; $Q(t)$ – is vector of load of reactive power source (RPS); $\dot{S}_{в}(t)$, $\dot{I}_{в}(t)$ – are vectors of powers and currents in branches of EES , where telemeasurements take place; $\dot{U}(t)$ – is vector of voltages in the nodes.

The first equation in (2) is equation of system state, solution of which satisfies initial condition $x_o = x(t_o)$ and gives vector of state $x(t)=\psi[x(t_o), u(t)]$. The second equation in (2) defines initial parameters depending on x(t) and u(t).

The task of optimum control of power fluxes in EES is to maintain the value F_* at defined zone of nonsensitivity δF_* (see Fig 2) (* means, that control is carried out in relative units, where optimum values of parameters are taken as the basis) [3]. For this purpose, at the output of the system control impacts over transformers are performed. The role of CT in control system is shown in Fig 2. Without CT all the actions aimed at introduction of optimality criterion F into optimality zone are performed by AT, that results in a great number of switchings of URL devices. By means of CT constant e. m. f. are introduced, which correct power fluxes in such a manner that optimally criterion value F approaches to minimum, moving away from the boundaries of optimality zone. As a result the number of URL AT switching decreases.

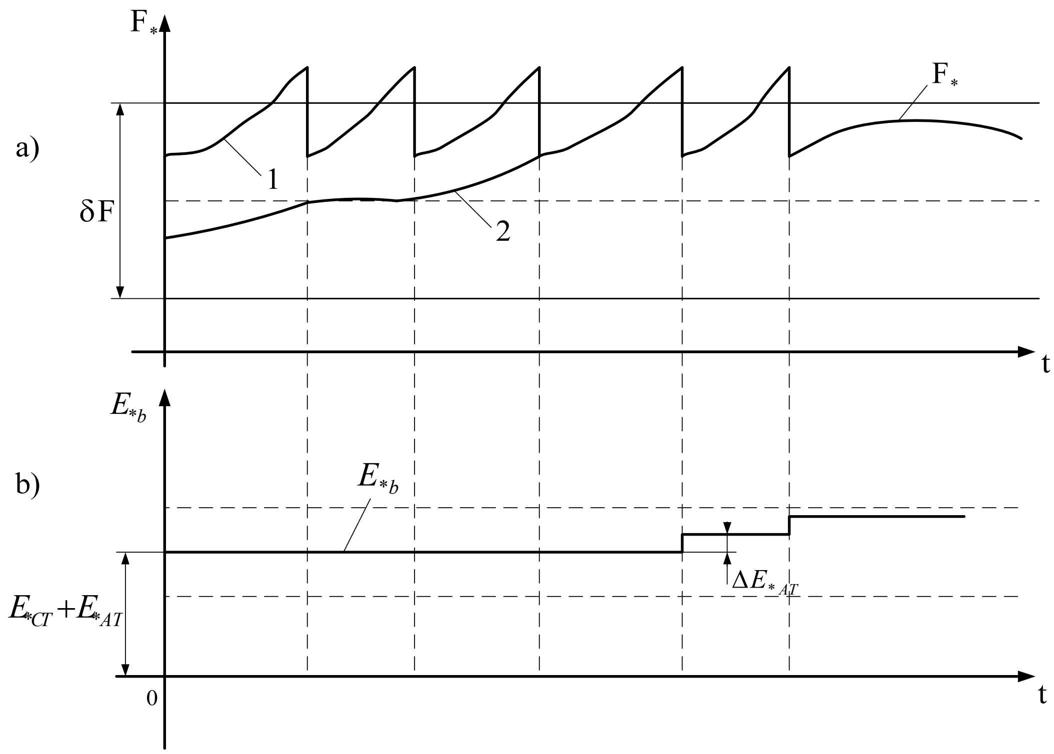

Fig. Change of : a) optimality criterion without CT (curve 1) and with CT (curve 2);
b) corresponding comparative e. m. f

To improve the efficiency of power fluxes control in EES in order to reduce power losses, it is necessary to reveal real possibilities of transformers with URL, evaluating sensitivity of power losses to changes of transformation ratios [5]. To enhance the efficiency of transformers with URL usage in EES in the process of control influences formation also it is necessary to evaluate their technical state and remaining resources.

Taking into account the above – mentioned, optimality criterion in the problem of EES mode operation can be established [6]:

$$F = \Delta P + P(\omega) + \sum_{i=1}^{q} P_{Ti} , \qquad (4)$$

where ΔP – are total losses of active power in EES; P(ω) – is power, equivalent to losses, as a result of non -supply of electric energy, due to failures of transformers, in particular, failures of URL; P_{Ti} – is penalty function, which is introduced for accounting of the transformer resource, including switchings of URL devices; q – is a number of transformers, being regulated.

Mathematical model and law of optimum control

In such problem set – up, control variables which are to be introduced by transformation ratios in all closed contours for realization of optimal current distribution are e. m. f and powers of RPS. In [3] it is shown, that optimum value of losses in EES is achieved at relative values of e. m. f, which are defined by formulas:

$$\underset{*\,ba}{E}(t) = \pi_a^e \underset{*\,p}{J}(t), \quad \underset{*\,br}{E}(t) = \pi_p^e \underset{*\,a}{J}(t), \qquad (5)$$

where $\underset{*\,ba}{E}(t)$, $\underset{*\,br}{E}(t)$ – are vectors of active and reactive components of relative values of balancing e. m. f, which introduce balancing currents $\dot{I}_{3p}$; $\underset{*\,a}{J}(t)$, $\underset{*\,p}{J}(t)$ – are vectors of active and reactive relative values of current nodes; π_a^e, π_p^e – are matrices of similarity criteria are defined by the formulas [3].

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

$$\pi_a^e = -\left[E_{ba}^{(б)}\right]_\partial^{-1} \nu r_в M_\alpha^{-1} \left[J_p^б\right]_\partial; \quad \pi_p^e = \left[E_{br}^б\right]_\partial^{-1} \nu r_в M_\alpha^{-1} \left[J_a^б\right]_\partial, \qquad (6)$$

where $\nu = N_\alpha x_{в\alpha} r_{в\alpha}^{-1} - x_к r_к^{-1} N_\alpha$ – is the matrix of system indices of EES inhomogeneity; $r_в$, $x_в$ – are diagonal matrices of branches resistance; $r_к$, $x_к$ – are diagonal matrices of contour resistance; M_α, N_α – are matrices of branches connections in nodes and contours of tree diagram.

E. m. fs are introduced in contours by joint action of AT and CT. Basic component of variable in time $E_{*зpb}$ of e.m.f of E_{CT} is introduced by means of CT to which e. m. f. of AT is added by ΔE_{*am} steps.

Taking into account the couplings between contour e. m. f. and transformation ratios of transformers at certain conditions (transformers in basic system of contours are in chords, the number of regulated transformers is equal to the member of contours) (5) can be written in the following form [3].

$$k'_{ct}(t) = 1 - E''_{*ct}(t), \quad k''_{ct}(t) = -E'_{*ct}(t),$$

$$k'_{at}(t) = 1 - E''_{*at}(t), \quad k''_{at}(t) = -E'_{*at}(t), \qquad (7)$$

where $k'(t), k''(t)$ – are vectors of real and imaginary components of transformation ratios of AT and CT, correspondingly.

System of automatic control and peculiar features of its functioning

In criterial form all parameters are given in relative units [4]. Then, the law of optimal control will be written:

$$u_*(t) = -\pi\, y_*(t), \tag{8}$$

$$r_{*i} = \begin{cases} +\Delta u_{*sp\ i} & if\ \ u_{*i} \ge u_{*i}^{+}; \\ 0 & if\ \ u_{*i}^{+} > u_{*i} > u_{*i}^{-}; \\ -\Delta u_{*sp\ i} & if\ \ u_{*i} \le u_{*i}^{-}, \end{cases} \tag{9}$$

where r_{*i} – is correcting actions of ACS, which lead the system in the zone of optimality (non sensitivity) in relative units (r.u.); $\Delta u_{*\ i}$ – is additive , which is added to setting point $u_{*sp\ i}$ i and caused corresponding actions of AT and CT aimed at introduction of controlled parameter in optimality zone; u_{*i}^{+}, u_{*i}^{-} - are upper and lower boundaries of nonsensitivity zone of u_{*i} in r.u. change, π - is, by its content, as it is shown in [3], matrix of similarity criteria; $u_{*i}=u_i/u_{io}$ – are parameters of RП, by means of which EES modes are optimized, in r. u. (optimal values of u_{io} parameters are taken as basic). Among possible methods of corresponding ACS realization method of adaptive regulation with reference model is widely used. Such an approach meets the requirements of EES normal modes control, numerous algorithms and programmes elaborated and applied in ASDC can be used within its frames. Such approach can be easily realized in practice by means of modern microprocessor systems. Structural diagram of optimum control of power fluxes in EES using similarity of optimal modes is shown in Fig 3.

The given control system comprises two contours. In the first contour (main) automatic control of separate AT and CT is performed by means of the devices of monitoring and control of autotransformers and cross transformers automatic functioning (AFACT). They operate in accordance with control laws (8) – (9). Observation vectors y' for AT and CT control are formed from telemeasurements in allocated correction region, where partial or complete observability is provided.

In the second contour (adaptation contour) depending on the degree of EES modes violation and supervisor decision actions aimed at AFACT devices resetting or direct control over AT and CT parameters can be taken. In the latter case, AFACT devices are used for coordination of telemechanics channel and control circuit of AT an CT. Supervisors orders regarding changes of transformation ratios are realized by means of corresponding change of vector components of correction actions **r** [4]. In case, when optimal control is performed automatically, matrices of similarity criteria π_a^e and π_r^e are defined in adaptation contour using complete information relatively EES state **y,** and, among them determining for the given CT similarity criteria. Their composition is defined by admissible computational error and realization of optimal transformation ratios. One more setting parameter is non sensitivity zone of transformation **ratio** δk_i, is set after the analysis of sensitivity of optimality criterion F to change of transformation criteria, applying the technique, suggested in [5].

In such a scheme reference model is a part of control system. At different stages of ACS implementation reference model can perform different functions. At initial stage of automation, when it is necessary to coordinate on – line control, performed by a supervisor with automatic control, it is a simulation model, the staff applies for analysis as well defines and corrects ACS setting parameters; application of the given model enables to simulate EES state and evaluate the results of control actions, including automatic actions. At the final stage, when optimum control of power fluxes in EES is performed mainly by local ACS, reference model becomes basic element of self – regulation and self analysis of ACS.

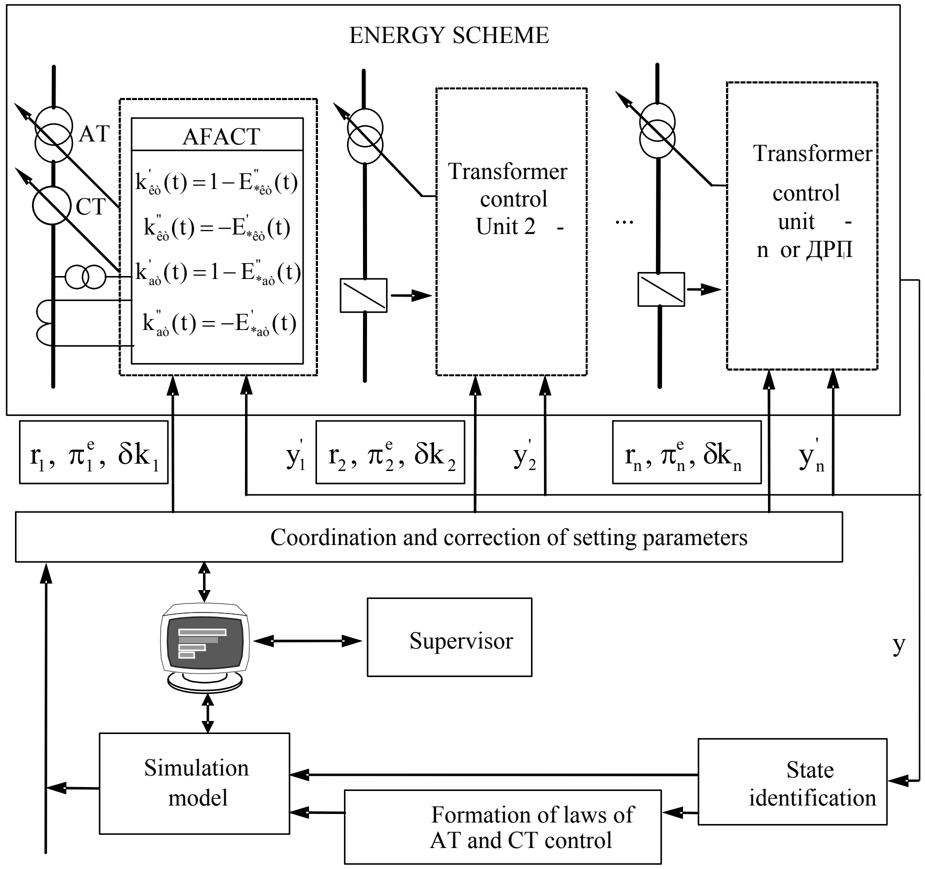

Fig. 3. Structural diagram of optimal control

Coordination of transformers operation at optimum control is performed in accordance with criterial dependencies $F_* = f(k_*)$. They show technical possibilities of transformers for control of power losses in EES and are used for determination of their influence on power fluxes. To divide transformers into functional groups and define the rate of each of them in power fluxes automatic control, the inverse sensitivity problem is solved [5 - 7]. As a result of its solution at the set nonsensitivity zone of optimum criterion δF_* non sensitivity zones δk_i of transformation ratios are defined. The dimensions of these zones correspond to real possibilities of the transformer to influence the losses. In accordance with their regulation effect different intensity 0of switching of EES transformers is determined. In such operation mode of control system introduction of EES mode in optimum region is realized by minimum possible number of control actions, that, in its turn, provides reliability and rational usage of regulating devices resources.

Example. Optimization of power flux distribution by means of cross – transformer on the example of the fragment of South – West EES (SWEES) scheme. Based on the foregoing procedure, relatively evaluation of power as a result interinfluence of EES electric networks modes, computation experiment aimed at additional losses reduction was performed on the example of the fragment of SWEES 110 – 750 kV scheme, shown in Fig 4. As the example, transit of power by SWEES networks from node 599 to node 945 is considered. Cross – transformer between buses of 330 kV of coupling auto transformer of distribution device HAPS and node 809 is introduced in the calculation scheme. It is assumed that transformation factor change at cross – transformer substation will be performed by stages 4, 6, 8, 12 and 16 of electric degrees.

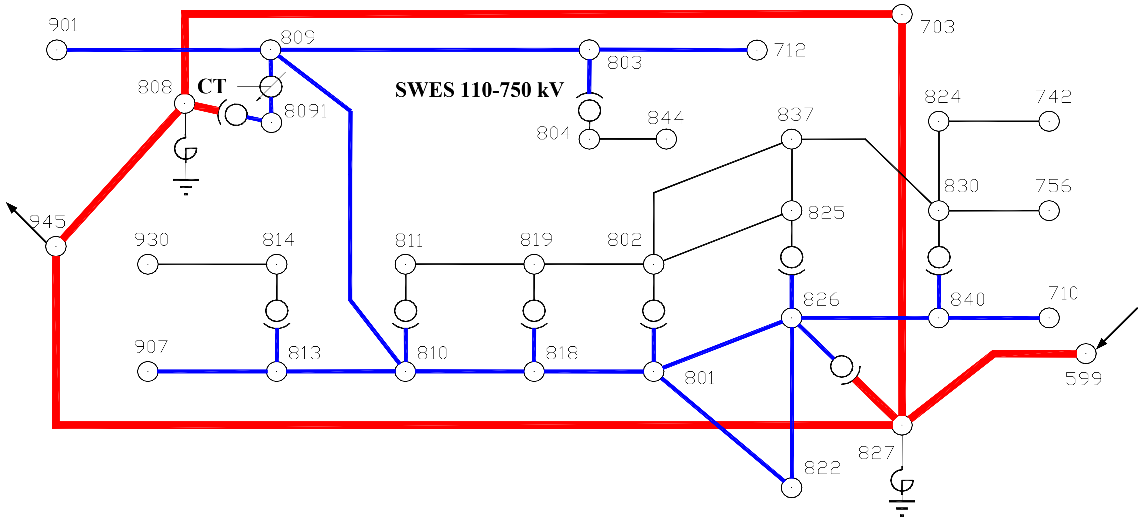

Fig. 4. Fragment of SWES 110-750 kV scheme

We use the method of directed exhaustive search for determination of optimum balancing e. m. f and transformation ratios of cross – transformers. For calculation experiment cross – transformer parameters, shown in [8] were applied. For comparison we will observe how power losses in networks change depending on the value of transit power flow prior to CT installation. Results of computations are shown in Table 1.

Table 1

Change of losses in EES depending on the value of power transit prior to CT installation

Transit, MWt	Losses of active power in lines, MWt			
	110	330	750	Σ
0	2,588	24,059	10,350	36,997
500	2,899	24,939	13,923	41,761
1000	3,312	26,287	26,635	56,234

To reduce these losses we will apply transversal component of transformation ratio by means of cross – transformer. We will load over – head transmission line 330 750 kV and unload transmission line110 kv.

After each measurement of power transit and cross – transformer angle measurement calculation of EES mode is performed, using the program of modes calculation “Graphscanner” and losses are calculated. As a result of calculations performed graphic dependencies of total system losses of active power on transformation ratios without transit and with transit of 500 and 1000 MWt are obtained (Fig 5).

Analyzing the obtained data we observe the influence of cross – transformer, that enables to unload the lines of lower voltage classes and load over – head transmission lines of higher voltage classes, losses in EES reduce. In order to define optimum transformation ratio of cross-transformer let us analyze the graph shown Fig 5. In accordance with this graph we obtain minimum overall system losses, if we set CT transformation ratio equal 8 or 8 electric degrees. While regulating transversal component of cross-transformer, voltage and frequency modes of EES are admissible.

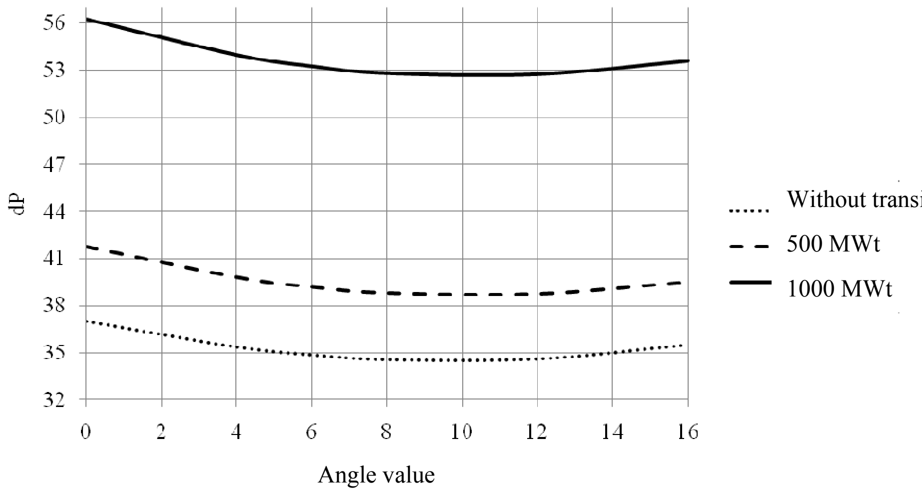

Fig. 5. Dependence of total system losses of active power on CT transformation ratio without and with transit of 500 and 1000 MWt

Electric networks of EES belong to different owners, that is why, mode optimization applying the criterion of overall system losses is not always expedient, regarding economic efficiency. Thus, we will consider the optimization applying the criterion of minimum losses of active power for separate electric network.

Let us analyze the dependence of active power losses in 110 kv electric lines on transformation ratio without transit and of 500 and 1000 MWt (Fig. 6).

As it is seen form Fig. 6, in case of transit absence and transformation ratio equal to 12 electric degrees losses in 110 kv electric lines are minor and are 1,859 MWt, that is for more less as compared with losses, appearing while calculation of the same electric circuit without CT. Losses were 2.588 MWt (see Table 1). Hence, we managed to reduce losses approximately by 0.729 MWt. In case of transformation growth up to 500MWt transformation ratio change enables to reduce losses in overhead transmission lines. As it is seen on the graph (Fig 6) these losses are the smallest, when transformation ratio corresponds to the angle of 16 electric degrees. They are 1,901 MWt, it is 1 MWt less if CT is not used.

When the transit is 1000 MWt, regulated by cross- transformer, i.e change of its transversal component of transformation ratio, losses were reduced by 1,3 MWt. At the given transit, transformation ratio of 16 electric degrees is the most efficient. Value of CT angle, when losses in 110 kV lines are the smallest does not coincide with the value of CT angle, at which total system losses were the smallest.

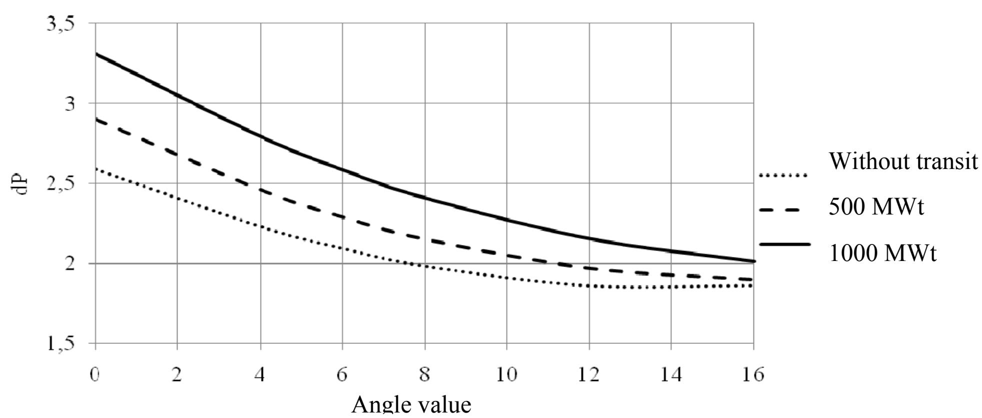

Fig. 6. Dependence of active power value losses in 110 kv electric lines on CT transformation ratio without transit and with transit of 500 and 1000MWt

Let us consider the dependence of active power losses value in 330 kv lines on transformation ratio of cross-transformer without transit and with transit of 500 and 1000 MWt (see Fig 7).

Both in lines of 110 kV and 330 kV when power transit is increased, losses change is observed in the lines. Change of CT transformation ratio led to decrease of losses in over-head transmission lines. As it is seen from Fig. 7, if the transit is absent and if the transit is 500 MWt angles 6, 8, 12 of electric degrees are optimum.

In overhead transmission line of 750 kV CT transformation ratio change did not influence considerably on losses value in the lines given voltage class, which is proved by curves, shown in Fig 8. These curves show the dependence of active power losses on the angle in lines of 750 kv, if transit is absent, and during the transit of 500 and 1000 MWT.

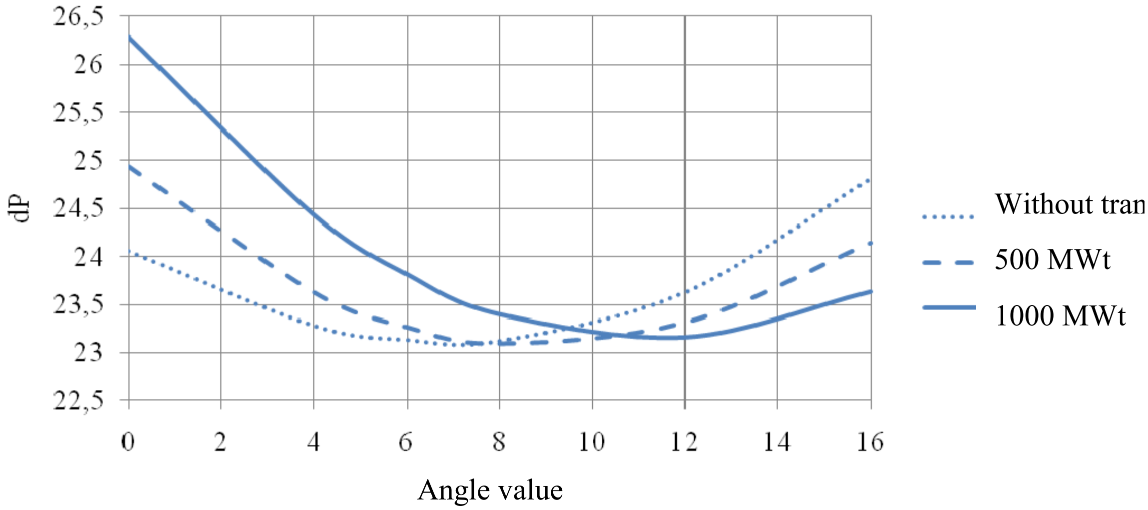

Fig. 7. Dependence of active power losses in 330 kv electric lines on CT transformation ratio without transit and with transit of 500 and 1000 MWt.

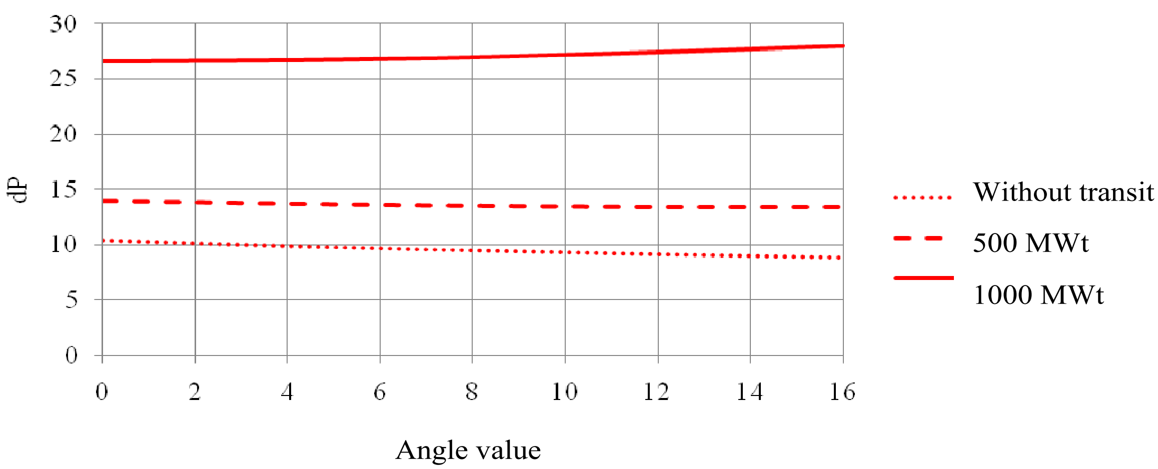

Fig. 8. Dependence of active power losses in 750 kv electric lines on CT transformation ratio without transit and with transit of 500 and 1000 MWt.

Conclusions

1. To obtain the desired effect from optimization of normal modes of EES the process of optimal control must be automated. Nowadays we have all the necessary conditions – hardware, software,

information support. Automation of optimum control of power fluxes and voltage in EES provides transition from sporadic to regular optimizing actions, that allows to reduce electric energy losses while its transformation by electric networks of EES.

2. While automation of optimum control of power losses in EES it is possible and expedient to apply the methods of the similarity theory and modeling. Based on these method it is possible to solve problems, characteristic for ASDC, proceeding form common methodological principles at all stages of optimum control. Such approach enables to construct adaptive ACS with decentralization of certain functions of ASDC practically without violation of principles of centralized control.

3.Usage of cross – transformer technologies allows to reduce additional losses, caused by unloading of main networks on the networks of lower voltage. Application of cross – transformers allows to enlarge the possibilities of active power fluxes control in EES possibilities of active power fluxes control in EES. Operation conditions of coupling autotransformer at electric stations and systems are improved

REFERENCES

1. Ольшванг М. В. Особенности кросс-трансформаторной технологии транспортирования энергии по сетям 110-765 кВ // Электро. – 2004. – №2. – С.52.

2. Лежнюк П. Д., Пауткина Л. Р. Подобие и расчет оптимального токораспределения в электрической сети // Изв. вузов. Энергетика. – 1989. – №2. – С. 51–53.

3. Лежнюк П. Д., Кулик В. В., Оболонский Д. І. Моделирование и компенсация влияния неоднородности электрических сетей на экономичность их режимов // Электричество. – 2007. – №11.– С. 2–8.

4. Мокін Б. І., Лежнюк П. Д., Лук'яненко Ю. В. Імітаційне моделювання в оптимальному керуванні нормальними режимами електричної системи // Вісник ВПІ. – 1995. –№ 3. – С. 5–9.

5. Воротницкий В. Э., Лежнюк П. Д., Серова И. А. Методика и программа оценки эффективности применения РПН и АРПН в замкнутых электрических сетях // Электрические станции. – 1992. – №1. – С. 60–66.

6. Астахов Ю. Н., Лежнюк П. Д. Применение теории подобия в задачах управления нормальными режимами электроэнергетических систем // Изв. АН СССР. Энергетика и транспорт. – 1990. – №5. – С.3–11.

7. Розенвассер Е. Н., Юсупов Р. М. Чувствительность систем управления. – М.: Наука, 1981. – 464 с.

8. Кулаков А. В., Ольшванг М. В., Савкин Д. А. Кросс-трансформаторная технология оптимизации потоков передачи и распределения энергии в сетях 110-765 кВ и ее технико-экономическое обоснование // VII Симпозиум: Электротехника 2010 год: Перспективные виды электротехнического оборудования для передачи и распределения электроэнергии. Сб. докл. – М.: ВЭИ-ТРАВЕК, 2003. – С. 1-6.

Lezhnyuk Petro – Doct. Sc (Eng.), Head of the Department of Electric Power Stations and Systems.
Vinnytsia National Technical University.

Jean-Piere Ngoma – assistant of the Department of Electric Engineering .
University of Duala ,Camerun.

Kilimchuk Anton –Master of the Department of Electric Power Stations and Systems
Vinnytsia National Technical University.