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IMPROVEMENT OF METHODS FOR MODELING AND CONTROL OF STEADY MODES OF POWER SYSTEMS

Specialty: 3341.01 - Power plants (electrical part)
and power systems
Branch of science: Engineering

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ABSTRACT
of dissertation for a scientific degree
Doctor of Science

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The dissertation work was carried out at the Azerbaijan Scientific-Research and Design-Prospecting Power Engineering Institute.

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GENERAL DESCRIPTION OF WORK

Relevance and of the development degree of the topic

Regarding with the widespread use of flexible AC transmission lines at the present stage of development of electric power systems management, it is required to develop new or update existing software for calculating and analyzing the steady modes of electric power systems (CSMPS) for the analysis, planning, to exploitation and assessment of the impact of FACTS on the modes of the electrical system.

CSMPS is the most frequently performed at all territorial and temporary levels of management and planning of modes. CSMPS have both independent significance and are an integral part of other complexes: maintaining an operational mode, analyzing the prospects for the development of networks, choosing of equipment, calculating of power and energy losses in electrical networks, calculating optimal modes, including taking into account power losses, in electrical networks ; calculation before emergency and post-emergency modes, as well as stability of modes of generator and load nodes of the system, including intersystem, long-distance transmissions, calculation of electromagnetic and electromechanical transients. On the operational control of the modes of EPS, it becomes necessary to perform a large amount of calculations related to the CSMPS. The solution of these problems requires multiple calculations of the mode, which makes increased requirements on the methods of calculating the steady state in real time in terms of speed and reliability of obtaining results in any operating conditions.

It should be noted that to calculate the steady modes of electrical systems, it is necessary to solve the system of nonlinear algebraic equations (SNAE) by numerical methods. Various numerical methods are used to solve the high-order SNAE for steady modes.

Many famous scientists, such as: Venikov V.A., Zhukov L.A., Bartolomey P.I., Voitov O.N., Gamm A.Z., Davydov V.V., Erokhin

P.M., Zhelezko Yu.S., Idelchik V.I., Sovalov S.A., Fazylov V.A., Krumm L.A., Melnikov N.A., Murashko N A.A., Okhorzin Yu.A., Tarasov V.I., Ayuev B.I., Pazderin A.V., Exposito AG, Monticelli A., B.F. Wollenberg, A.J. Wood have made a significant contribution to the development of methods and algorithms for calculating steady-state modes of electric power systems.

At the Azerbaijan SR and DP PE Institute, a group led by professors O.S. Mamedyarov and A.B. Balametov, effective algorithms and programs for calculating the steady-state modes of electrical networks have been developed, which ensure high reliability of convergence, effectiv use of computer RAM by using: Seidel's method with secondary correction; high-speed method with deviding; second order methods, as well as methods of stochastic approximation with a probabilistically given initial information.

The use of artificial intelligence methods opens up new possibilities for the use of personal computers in the management of power systems taking into account of the FACTS. Artificial neural networks (ANNs) make it possible to replace the steady state mode calculations with its approximation, rid of the need for iterative calculation schemes.

It is required to develop methods, algorithms and software for simulating the targeted separation of flows and power losses between the EE market participants regarding with the introduction of competitive relations in the electrical power market.

The main criteria for the wholesale electricity market are the maximum profit from the sale of electrical power or the minimum cost of energy resources required for the production, transformation, transmission and distribution of power. This requires of the development of traditional methods, algorithms and optimization tools.

A significant excess of actual losses over technical ones requires the improvement of accounting systems, research and development work on the calculation, analysis, rationing and reduction of losses

Implementation of information and communication technologies in the electric power industry in recent years makes it possible to determine the total losses of active power in an extra-high voltage overhead line (EHV OHL) by measuring active powers at the ends of the line and by selecting based on this, the power losses on corona and on heating of wires.

The researches of I.V. Zhezhelenko, Yu.S. Zhelezko, I.I. Kartashev, B.I. Kudrin, A.K. Shidlovsky, O.S. Mamedyarov and other scientists are devoted to the complete solution of the EE quality problem. Some problems in the field of energy efficiency are currently awaiting their final solution due to the influence on the quality of electricity by consumers themselves.

New intelligent technologies require the development of methods for modeling the overhead line (OHL) mode, based on synchronized vector measurements (SVM) and corresponding their accuracy.

Object and subject of research

The object of research is the electric power system.

The subject of the research is the steady-state modes of electric power systems.

The purpose of the work and objectives of the study

The purpose of the dissertation is to improve the methods of modeling and control of steady-state modes of power systems to increase the efficiency and economy of its operation, taking into account of new intelligent technologies (FACTS devices and synchronized vector measurements - SVM) and of the requirements of the electrical power market.

In accordance with the formulated goal, the following main problems are solved in the dissertation work:

1. Modeling of steady-state electrical network modes by applying FACTS devices.
2. Modeling of steady-state modes of an electric network using ANN.

3. Development of recommendations on diagnostics of the causes of divergence or lack of a solution in calculations of steady-state modes based on the analysis of the initial data, scheme and regime.

4. Development of algorithms for modeling address separation of flows and power losses between EE market participants.

5. Development of algorithms for optimization of EPS modes taking into account FACTS.

6. Development of algorithms for predicting power losses in electrical networks.

7. Modeling of variable losses in distribution electric networks, and obtaining new formulas for assessment of variable losses of EE both for normal circuits and modes, and for power supply to consumers with restrictions and interruptions.

8. Operational measuring of the mode parameters at the ends of the EHV overhead line and the development of algorithms for identifying active power loss components.

9. Development of a method and algorithm for modeling the overhead line mode, based on synchronized vector measurements and the corresponding accuracy of SVM.

10. Development of a non-iterative method for assessing the state of EHV transmission lines.

Research methods

In the dissertation work, when solving the assigned problems, the following were used: methods of the general theory of electrical systems, optimization methods, probability theory and statistical methods.

The main provisions, presenting for defense

1. Results of computer modeling of the assessment of the influence of FACTS devices on the EPS modes.

2. Results of CSMPS taking into account the dependence of the active resistances of the overhead line wire on the ambient temperature and currents in the branches for the equivalent circuit of Azerenerji OJSC and a modified version of the IEEE test system.

3. Results of the study of complete and simplified models of FACTS devices on examples of complex electrical networks.

4. Methodology for diagnosing the reasons for the divergence or absence of a solution based on the analysis of the initial data, the scheme and the mode before and in the process of solving the SME.

5. Methodology, software and results of CSMPS applying ANN.

6. Algorithms and program for address distribution of active and reactive power flows and active power losses.

7. Methodology, algorithm and program for optimizing the EPS mode based on sequential linearization of the objective function and constraints by using the linear programming method taking into account FACTS devices.

8. Algorithm and program for the economy distribution of the load between power plants by applying an artificial neural network of Hopfield.

9. Methodology for determining variable losses by simulation modeling of schedules of electrical loads on duration.

10. Methodology, algorithm and program for predicting power losses in the electrical network, based on regression dependencies.

11. A system for measuring simultaneous measurements of the mode parameters at the ends of the extra high voltage OHL and the identifying of component losses.

12. Method and algorithm for modeling the OHL mode, based on synchronized vector measurements and the corresponding accuracy of the SVM.

13. The method allows to solve the problem of the SE of the EHV transmission line in a non-iterative way.

Scientific novelty of research

1. A methodology, algorithm and software were developed for the analysis, planning and control of steady-state modes of EPS, taking into account FACTS devices using the DELPHI computer software complex.

2. An algorithm for determining and accounting of the temperature of wires of OHL at calculating of the flow distribution in electrical networks developed and implemented

3. The stages of formalization of the CSMPS task by using ANN worked out, a methodology and software have been developed for CSMPS with the use of ANN by applying of the computer program system DELPHI.

4. A inputting method of the PU calculated nodes developed to obtain a physically realizable solution for the equations of the steady-state mode of an electric network with an EHV transmission line.

5. A methodology and an algorithm developed, that are implemented and the tasks of address distribution of power flows, in the form of software in the MATLAB environment. The analysis of methods of adressness of flows and losses of active capacities by matrix methods, decomposition method, as well as loss separation based on the Z-matrix method and the marginal method is carried out.

6. The model for applying of the iterative procedure of sequential linearization of the objective function and restrictions by using of linear programming for solving of the optimization problem taking into account FACTS devices has been improved.

7. Issues of optimization of the EPS mode by active power in the wholesale market have been worked out, a program has been developed based on the coordinate descent method, taking into account the restrictions in the form of inequalities. An algorithm and a program have been developed using an artificial neural network of Hopfield for the economy distribution of the load between power plants.

8. For the first time, a method and an algorithm for optimizing the EN mode were developed based on obtaining regression equations for flows and power losses on parameters, taking into account controlled FACTS.

9. The problem of determining the energy of variable losses and evaluating of the intervals of changes in losses by simulating the

schedules of electrical loads in the form of an exponential function has been formulated and solved.

10. The methods, algorithms and programs for constructing regression dependencies based on the results of simulation modeling and by applying of statistical methods for planning of an experiment, the least squares method and artificial neural networks have been developed.

11. Requirements to the systems for an operational assessment of active power losses based on the current parameters of the mode at the ends of OHL have been formulated.

For the first time, a specialized measurement system was used to conduct experimental studies on the identifying of corona losses by measuring the mode parameters at the ends of a 500 kV overhead line.

12. A method and an algorithm for estimating the state of OHL based on synchronized vector measurements, which correspond to an accuracy of the SVM, are proposed.

13. A method that allows solving the problem of assessment of the state in a non-iterative way has been developed.

The theoretical and practical value of the research

The results obtained in the dissertation have both theoretical and practical significance.

The theoretical value of the results obtained in the dissertation work are modeling the steady-state modes of power systems taking into account of the FACTS devices, wire temperature, applying of artificial neural networks, the input of PU calculated nodes to obtain a physically realizable solution for the equations of the steady-state mode of an electric network with an EHV transmission line, the development of a method for address distribution of flows and power losses, development of a methodology and algorithm for optimization of the EN mode based on obtaining regression equations for flows and power losses from parameters taking into account controlled FACTS, development of a methodology, algorithm and program for obtaining regression dependencies using statistical methods, and an algorithm for estimating the state of overhead lines that correspond to the accuracy of the SVM.

The practical value of the results obtained in the dissertation work is in the fact that methods and algorithms were developed, implemented in the form of software tools for calculating and optimizing steady-state modes, predicting electricity losses in electrical networks, assessing the state of an extra high voltage power transmission line.

Approbation of dissertation work

The main provisions of the work were reported and discussed at: annual seminars of AzSR and DP PE Institute and received a positive assessment at scientific forums: Republican and international scientific and practical conferences "Problems of Cybernetics and Informatics" 2003, 2004, 2008 and 2010 in Baku; International scientific and technical conferences "Transmission of energy by alternating current over long and ultra-long distances", 2003, Novosibirsk, Russia; International Conference on Technical and Physical Problems in Power Engineering, held in 2004-2021. in Iran, Turkey, Romania, Azerbaijan, etc.; The X scientific and technical conference "Electromagnetic compatibility of technical equipment and electromagnetic safety EMC-2008", St.-Petersburg, 2008; III International scientific-practical conference "The role of scientific innovation in the development of the country's economy", Baku, 2009; All-Russian scientific-practical conference with international participation, Moscow, 2009; "Oil and culture as the property of the people." International scientific-practical conference dedicated to the 90th anniversary of the Azerbaijan State Oil Academy. Baku, 2010. "The role of scientific innovation in the development of the country's economy" International scientific-practical conference, 2010; International Scientific and Practical Conference: Fedorov Readings.

All-Russian scientific and practical conference (with international participation) Moscow, 2010-2019; International conference "Energy of Moldova" 2012 and 2016, Republic of Moldova; International Scientific Seminar. Yu.N. Rudenko "Methodological issues of researching of the reliability of large power systems" Baku, Azerbaijan 2012 and Kazan, 2020; 2nd World Conference on Soft Computing dedicated to the research heritage Lotfi A. Zadeh. Baku, Azerbaijan, 2012; "Modern scientific, technical and applied problems of power", 2015, SSU; 18th IFAC Conference on Technology, Culture and International Stability TECIS 2018, Baku; International scientific-practical conference with elements of a scientific school, Moscow, 2019; The 6th and 7th International Conference on Control and Optimization with Industrial Applications Volume II, 2018 and 2020, Baku, Azerbaijan.

Application of work

The proposed formulas, methods and algorithms are used for: calculations and optimization of steady-state modes; for calculations, forecasting, monitoring of technical and commercial losses of electricity and determination of norms for losses in supply and distribution networks in 2000-2021; determination of power disbalances at power plants "Azerenerji" in 2004; assessing the influence of FACTS devices on the modes of the Azerbaijan EPS; studies of the influence of abruptly varying load in the deterioration of the quality indicators of EE at HV substations in 2007, 2010, 2011; experimental studies of simultaneous measurements of mode parameters at the ends of 500 kV transmission lines in 2008. On the basis of research carried out on the topic of the thesis, 3 patents for inventions, 5 copyright certificates for the developed software were obtained. The developed and obtained solutions in the dissertation allow to increase the efficiency of the EPS operation.

Publications

On the topic of the dissertation, 140 publications have been published, including 3 monographs, 30 research reports have been completed, 5 articles indexed in the scientometric database Web of Science, 6 articles indexed in the scientometric database Scopus.

Name of the organization where the work carried out

Research and development were carried out on the basis of plans approved by the Azerenerji system and included in the reports of the Steady Modes of Power Systems Department of the Azerbaijan Scientific-Research and Design-Prospecting Power Engineering Institute in 2000-2021.

Structure and scope of work

The dissertation work consists of an Introduction, six chapters, a bibliography of 267 titles, Appendices, a list of abbreviations, 90 figures, 68 tables and consists of 570000 characters. In particularly, Chapter I consists of 72000 characters, Chapter II of 84000 characters, Chapter III of 64000 characters, Chapter IV of 76000 characters, Chapter V of 86000 characters, Chapter VI of 56000 characters.

THE CONTENT OF THE WORK

In the introduction of the dissertation work, a general description of the work is presented: the relevance is shown, the goals and objectives of the research, scientific novelty, practical value, structure and volume of work are reflected.

In first chapter is considered of the modeling of FACTS devices in the calculations of steady-state modes of EPS (Fig. 1-3) The modeling methods used to model FACTS devices can be built on the joint and separate solution of the corresponding SSM equations.

In the sequential method, nodal stresses and angles as state variables are solved by Newton's method, after that to update the state variables of controlled devices, a subproblem is solved at each step.

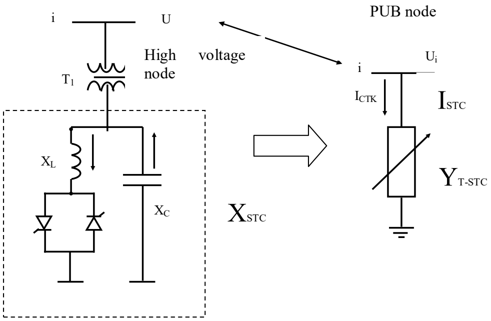


Fig. 1. Thyristor-controlled static compensator

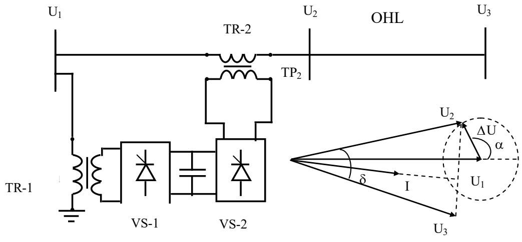


Fig.2. Schematic representation of UPFC

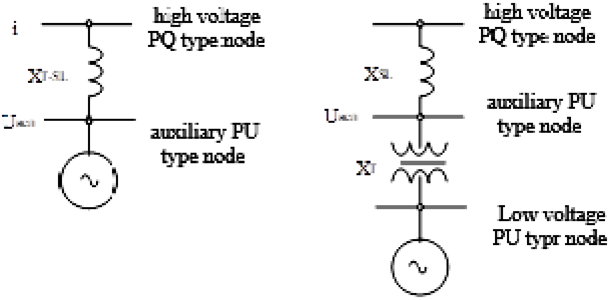
The second approach includes the state variables describing the FACTS and ES devices in a single system of equations

$$f(U_i, \delta_i, X_{FACTS})=0$$

where U_i, δ_i - voltages and phase angles in nodes; X_{FACTS} - corresponds to the state variables of FACTS devices

In the injection model, FACTS devices are considered as devices that determine given equivalent active and reactive power values in a node.

Model of the total conductance interprets devices



a) b)

Fig. 3. Static models of STC: a) 2 nodes b) 3 nodes

FACTS as shunts or longitudinal elements with a total conductivity B.

The ignition angle model includes the dependence of total rezistance of FACTS or power values on the variable ignition angles of the semiconductor switches. The ignition angle is considered as a state variable

$$B_{ij}^{-1} = X_{ij} = f(\alpha(X_L, X_C) \text{ and } P_{ij}, Q_{ij} = f(\alpha, X_L, X_C).$$

$$B_{STC} = B_C - B_{TVP} = -\frac{1}{X_C \cdot X_L}\left\{X_L - \frac{X_C}{\pi}\left[2(\pi-\alpha)+\sin(2\alpha)\right]\right\} \quad (1)$$

Accounting for FACTS devices requires input some changes in the usual SM algorithms. For example, UPFC consists of two parallel and series voltage sources

$$E_{par} = U_{par}\left(\cos\Delta\delta_{par} + j\sin\Delta\delta_{par}\right) \tag{2}$$

$$E_{ser} = U_{ser}\left(\cos\Delta\delta_{ser} + j\sin\Delta\delta_{ser}\right) \tag{3}$$

Here, U_{par}, δ_{par} – are the module and the phase angle of a parallel voltage source having regulation limits $U_{par.min} \leq U_{par} \leq U_{par.max}$ and $0 \leq \delta_{par} \leq 2\pi$; U_{ser}, δ_{ser} - module and the phase angle of a series voltage source having regulation limits $U_{ser.min} \leq U_{ser} \leq U_{ser.max}$ and $0 \leq \delta_{ser} \leq 2\pi$, respectively.

The mathematical model of the UPFC at the CSMPS has the form[1]:

Active and reactive power at node i:

$$\begin{aligned}
P_i &= U_i^2 g_{ii} + U_i U_j \left[g_{ij}\cos(\delta_i - \delta_j) + b_{ij}\sin(\delta_i - \delta_j)\right] + \\
&\quad + U_i U_{ser}\left[g_{ij}\cos(\delta_i - \delta_{ser}) + b_{ij}\sin(\delta_i - \delta_{ser})\right] + \\
&\quad + U_i U_{par}\left[g_{vR}\cos(\delta_i - \delta_{par}) + b_{ij}\sin(\delta_i - \delta_{par})\right] \\
Q_i &= -U_i^2 b_{ii} + U_i U_j \left[b_{ij}\sin(\delta_i - \delta_j) - b_{ij}\cos(\delta_i - \delta_j)\right] + \\
&\quad + U_i U_{ser}\left[g_{ij}\sin(\delta_i - \delta_{ser}) - b_{ij}\cos(\delta_i - \delta_{ser})\right] + \\
&\quad + U_i U_{par}\left[g_{par}\sin(\delta_i - \delta_{par}) - b_{ij}\cos(\delta_i - \delta_{par})\right]
\end{aligned} \tag{4}$$

At node j:

$$\begin{aligned}
P_j &= U_j^2 G_{jj} + U_j U_i \left[G_{ji}\cos(\delta_j - \delta_i) + B_{ji}\sin(\delta_j - \delta_i)\right] + \\
&\quad + U_j U_{ser}\left[G_{jj}\cos(\delta_j - \delta_{ser}) + B_{jj}\sin(\delta_j - \delta_{ser})\right] \\
Q_j &= -U_j^2 B_{jj} + U_j U_i \left[G_{ji}\sin(\delta_j - \delta_i) - B_{ji}\cos(\delta_j - \delta_i)\right] + \\
&\quad + U_j U_{ser}\left[G_{jj}\sin(\delta_j - \delta_{ser}) - B_{jj}\cos(\delta_j - \delta_{ser})\right]
\end{aligned} \tag{5}$$

For branch with series (longitudinal) source:

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[1] Acha, E. FACTS. Modelling and Simulation in Power Networks / E. Acha, R. Claudio, H. Fuerte-Esquivel [and ets.] // - John Wiley & Sons, LTD, -2004. - 420 p.

$$\begin{aligned} P_{ser} &= U_{noc}^{2} g_{jj} + U_{ser} U_{i} \left[g_{ji} \cos(\delta_{ser} - \delta_{i}) + b_{ji} \sin(\delta_{ser} - \delta_{i}) \right] + \\ &+ U_{ser} U_{j} \left[g_{jj} \cos(\delta_{ser} - \delta_{j}) + b_{jj} \sin(\delta_{ser} - \delta_{j}) \right] \\ Q_{ser} &= -U_{ser}^{2} b_{jj} + U_{ser} U_{i} \left[g_{ji} \sin(\delta_{ser} - \delta_{i}) - b_{ji} \cos(\delta_{ser} - \delta_{i}) \right] + \\ &+ U_{ser} U_{j} \left[g_{jj} \sin(\delta_{ser} - \delta_{j}) - b_{jj} \cos(\delta_{ser} - \delta_{j}) \right] \end{aligned} \tag{6}$$

For the parallel source at node:

$$\begin{aligned} P_{par} &= -U_{nap}^{2} G_{par} + U_{par} U_{i} \left[G_{par} \cos(\delta_{par} - \delta_{i}) + B_{par} \sin(\delta_{par} - \delta_{i}) \right] \\ Q_{par} &= U_{noc}^{2} B_{ser} + U_{par} U_{i} \left[G_{ser} \sin(\delta_{par} - \delta_{i}) - B_{par} \cos(\delta_{par} - \delta_{i}) \right] \end{aligned} \tag{7}$$

Under the assumption that for the UPFC without losses, the active power consumed by the parallel source is equal to the active power consumed by the longitudinal source $P_{par} + P_{ser} = 0$.

To maintain a given active and reactive power transmitted through the line between nodes *i* and *j* by regulating the emf in UPFC are added linearized power flows equations:

$$\begin{aligned} \Delta P_{ij}^{E''_{UPFC}} &= P_{ij}^{contUPFC} - P_{ij}^{E''_{UPFC},calc.} \\ \Delta Q_{ij}^{E'_{UPFC}} &= Q_{ij}^{contUPFC} - Q_{ij}^{E''_{UPFC},calc.} \end{aligned} \tag{8}$$

where $P_{ij}^{contUPFC}$ and $Q_{ij}^{contUPFC}$ - adjustable values of flows of active and reactive power of the branch; $P_{ij}^{X_{UPFC},calc}$ and $Q_{ij}^{E''_{UPFC},calc}$ - calculated values of branch power flows; $\Delta P_{ij}^{E''_{UPFC}}$ and $\Delta Q_{ij}^{E'_{UPFC}}$ - power flows disbalances.

Equations (2-8) constitute the mathematical model of the UPFC at the CSMPS.

A simplified representation of FACTS in the form of an equivalent transformer with a complex transformation ratio or in the form of additional determining currents is considered. The program, CSM has been modernized, modules for automated variant calculations, active power approximation and solution search with correction of the branch flow have been added. The programs have been tested by computer modeling of the SM on test and real examples with STC, TCR, TCSC, UPFC.

Calculations were carried out to assess the effectiveness of TCFT application in the ring heterogeneous 220-330-500 kV network of Azerenerji JSC. According to the calculation results, the reduction in total losses is 3.14 MW. Calculations have been made taking into account STC and TUR for the 220-330-500 kV scheme of the EPS of Azerbaijan. Active and reactive power flows are shown in Fig. 4, nodal stresses and angles are presented in Table 1.

Table 1

CSM results when installing TCR in the 4th node

Nodes voltages	Electrical nerwork nodes						
	1	2	3	4	5	6	7
|U|, kV	510.0	337.00	337.06	500.0	334.46	221.34	225.79
δ, deg.	0.00	0.09	-0.01	-5.56	-6.20	-8.14	-1.37

The calculations of the SM were also carried out in the case of installation in the 6th node of the STC with the limits of reactive power regulation +121÷-242 MVAr.

To maintain the voltage 220 kV in the 6th node for a load mode of 1200 MW, the STC generates 92.86 MVAr of reactive power. In this case, the angle of ignition of thyristors is $\alpha_{STK} = 93.91^0$. To maintain the flow in a 500 kV transmission line equal to 800 MW when using TCSC, X_{TUK} = 44 Ohm is required. In this case, the angle of ignition of thyristors is equal to $\alpha = 102.95^0$. The connecting of a TCSC between nodes 1 and 4 of the transmission line supports to an increase in the power transmitted on the 500 kV OHL to 779.47 MW.

This suppors to unloading of power lines 2-5, 2-3, 7-6. For example, a 220 kV double-circuit transmission line is unloaded from 234 MW to 178 MW. The sum losses of active power in this mode are reduced by 2.07 MW. Modeling of the UPFC was carried out on the scheme 220-330-500 kV of the EPS of Azerbaijan (Fig. 4) for a load mode of 1200 MW at node 6, the results of the calculation are presented in Table 2.

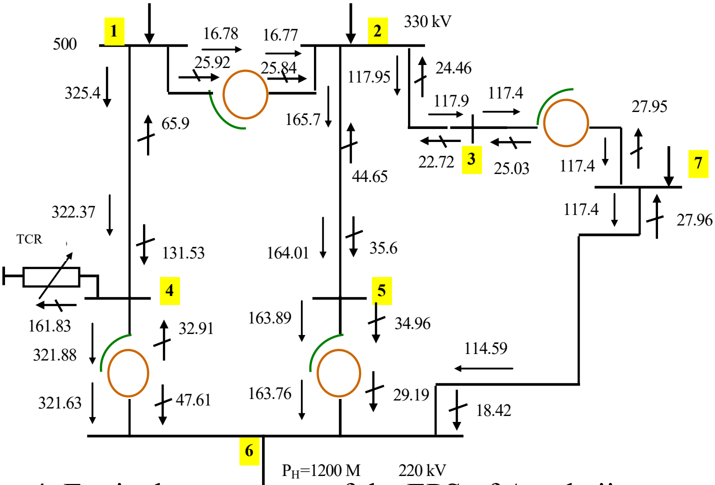

Figure 4. Equivalent segment of the EPS of Azerbaijan

Table 2

The results of the CSM at the operation of the UPFC in 220 kV line

№	UPFC K_t 7-8	Ignition angle, α	P_{14}, MW	P_{25}, MW	P_{76}, MW	ΔP_{load}, MW	ΔP_{sum}, MW
1	1+j0	Initial	687.74	339.58	204.07	31.39	32.73
2	1-j0.15	Optimal	737.01	368.95	123.71	29.00	30.70
3	1-j0.35	Max flows	801.43	405.44	25.21	31.54	33.24

Connecting to the UPFC between nodes 7 and 6 of the power transmission line with K_t = 1-j0.35 supportes to an increase in the power transmitted through the 500 kV OHL to 800 MW, while the shift angle is -19.5 degrees. At the same time, a 220 kV transmission line is unloaded from 204 MW to 25 MW. The optimal mode is achieved at the shift angle is -10.2°.

It established that the use of FACTS devices in 220-330-500 kV power plants can significantly increase the transmitted active power, improve voltage levels and reduce active power losses within 4.37÷7.57 MW. In adition, that the most effective and top-priority measure in terms of maintaining voltages and reducing active power losses is the installation of the STC on the buses of the Absheron 220 kV substation and the UPFC in the 220 kV Mingechaur-Absheron OHL.

The results of the first chapter were reflected by the author in the works [21, 34, 26, 37, 38, 42, 45, 50, 52, 55].

In the second chapter, the modeling of stationary modes of electrical networks applying of the traditional equations of the steady state mode and heat balance is carried out.

This study is due to the fact that the continuous increase in the load in electrical networks requires reliable information about the state of the line, as well as actual data on the temperature of the wires and the density of the flowing current to maximize the use of the throughput of overhead lines (OHL).

The heat balance equation for the steady-state thermal regime of the OHL is written as follows:

$$I^2 \cdot R_{20} \cdot \left[1 + \alpha \cdot \left(t_{np} - 20\right)\right] + P_c = \pi d_{np}\left(k_{\text{К}} + k_{\text{Л}}\right)\left(t_{np} - t_{в}\right)$$

in given equation I - is the line current, A; R_{20} - wire resistance at 20° C, Ohm/m; α - temperature coefficient of wire resistance, 1/°C; t_w - wire temperature, °C; t_a - air temperature, °C; k_k, k_l - is the heat transfer coefficient of the wire during convective and radiant heat exchange, W/(m^2°C); P_c - is the heat of solar radiation absorbed by 1 m of wire per unit of time, W; d_w - wire diameter, m.

The steady-state equations taking into account the temperature dependence differ from the traditional Newton-Raphson method in that the temperature dependences are taken into account in the conductivity:

$$P_i\left(\delta,U,t_{\text{пр}}\right)=V_i\sum_{j=1}^{n}V_j\left(G_{ij}\left(t_{\text{пр}}\right)\cdot\cos\left(\delta_i-\delta_j\right)+B_{ij}\left(t_{\text{пр}}\right)\cdot\sin\left(\delta_i-\delta_j\right)\right)$$

$$=P_{\text{г},i}-P_{\text{н},i}$$

$$Q_i\left(\delta,U,t_{\text{пр}}\right)=V_i\sum_{j=1}^{n}V_j\left(G_{ij}\left(t_{\text{пр}}\right)\cdot\sin\left(\delta_i-\delta_j\right)-B_{ij}\left(t_{\text{пр}}\right)\cdot\cos\left(\delta_i-\delta_j\right)\right)=$$

$$=P_{\text{г},i}-P_{\text{н},i}$$

$$H_{ij}(\delta,U,t_w)=t_{ij}-\left(T_a+\mathrm{R}_{\theta,\mathrm{ij}}\cdot g_{ij}(t_w)\cdot\left(U_i^2+U_j^2\right)\right)-2g_{ij}(t_w)\cdot U_i\cdot U_j\cos\left(\delta_i-\delta_j\right)$$

CSMPS were applyied for two test systems taking into account the temperature dependence of active resistance:

1. 7-nodes equivalent circuit of 110 kV section of the Azerbaijan Power system (Fig. 5).
2. Modified version of the IEEE 6-nodes test circuit.

Table 3 shows the results of a comparative analysis of CSMPS for an equivalent circuit with 7 nodes.

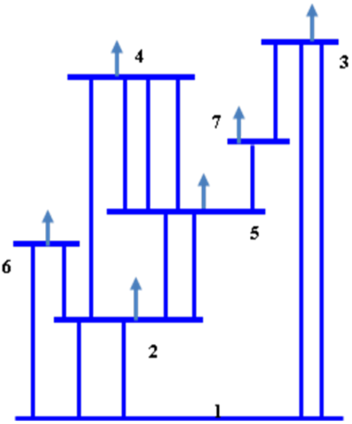

Figure 5. 7-nodes equivalent circuit on 110 kV

Taking into account the temperature dependence in the SME increases the losses in the loaded lines. The total losses for the traditional CSMPS amounted to about 4.4 MW, and taking into account the temperature 4.55 MW and 4.67 MW.

Table 3

Results of the comparative analysis of the steady mode calculation for the equivalent circuit with 7 nodes

Branches	Power, MVA	T_w, ^{0}C	Relative increasing of resistance, %	Results of power losses in CSMPS		
				Traditional, MW	Taking account of temperature, MW	Relative increasing of power,%
1-2	86.6	40.9	6.40	1.01	1.0703	5.97
1-2	86.6	40.9	6.40	1.01	1.0703	5.97
1-3	45.4	34.9	1.62	0.5537	0.5653	2.09
1-3	45.4	34.9	1.62	0.5537	0.5653	2.09
1-6	58.6	33.9	3.57	0.0701	0.073	4.14
2-4	57.7	34	0.77	0.1276	0.1318	3.29
2-5	68.1	29	4.00	0.4682	0.4843	3.44
2-5	68.1	29	4.00	0.4682	0.4843	3.44
2-6	33.1	27.9	3.63	0.0516	0.054	4.65
5-4	17.9	26.9	0.10	0.0113	0.0113	0
5-4	14.4	26	0.10	0.0113	0.0113	0
5-4	10.8	25.2	0.05	0.0011	0.0011	0
5-7	10.8	25.2	0.39	0.0471	0.0485	2.97
7-3	8	25.1	1.15	0.0119	0.0123	3.36
Total losses				4.3959	4.5831	4.26

The relative change in losses for loaded lines was about 8.8%. The total loss of circuit changed by 6.3%. Calculations were also carried out for case of: $T_{air} = 40^oC$, $t_{over} = 25$. For given case, the total losses were 4.721 MW. The change in losses for loaded lines was about 11.2%.

The CSMPS problem is reduced to minimizing the sum of the squares of the nodal power disbalances[2]:

$$\sum_i (S_i(U,\delta) - S_i)^2 \to \min$$

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[2] Khokhlov, M.V. Raschety ustanovivshikhsya rezhimov EES s ispol'zovaniyem neyronnykh setey // Novyye informatsionnyye tekhnologii v zadachakh operativnogo upravleniya elektroenergeticheskimi sistemami. - Yekaterinburg: Ur B of RSA, -2002. –c.102–126.

where $S_i = P_i + jQ_i$

A methodology and software for CSMPS with applying of ANN in the Delphi environment has been developed, the block diagram of which is presented in Fig.6. CSMPS with applying of ANN was tested on a test example of a 6 nodes circuit (Fig. 7).

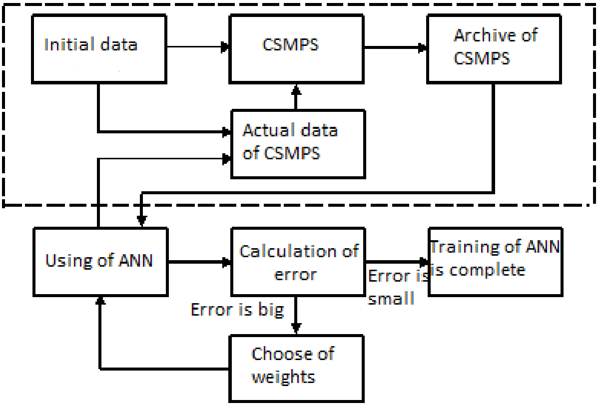

Figure 6. Block diagram of program of application of ANN for CSMPS

For training and testing, loads were generated in the range from 0% to 100%, and in PU nodes the values of voltage modules from 0.9 to 1.1, active power was generated on 50% and 100%. It was determined that the size of the training sample in the range of 200-300 provides an acceptable accuracy of CSMPS on applying ANN.

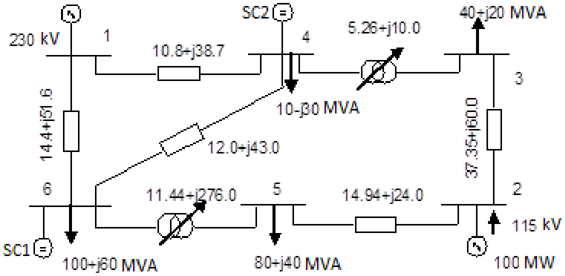

Figure 7. 6-nodes test circuit

It was found that for modes closly to the limits of static stability, the intervals of change in operating parameters should be taken as less than 5-10% compared to the initial mode. The reliability and accuracy of the results of calculating of the SM applying ANN were verified by comparison with the results of the well-known CSM programs.

In this chapter of the dissertation, studies of adaptive algorithms for seeking of solutions for steady-state modes of increased reliability were carried out.

The most frequently encountered in practice reasons for the absence of a solution to the SME by known methods and programs are the following: errors in specifying the initial information; poor conditioned system of equations: large condition numbers, poor measurements, small resistances; presence of EHV overhead transmission lines; the proximity of the regime to the limits of static stability; incompatibility of the system of nonlinear equations of the steady-state mode; the presence of several, including the technically unacceptable solutions; negative resistances, EN heterogeneity, poor choice of initial approximations of dependent variables.

To build an adaptive algorithm for obtaining a solution, it is relevant to formalize of separate stages: diagnostics of the reasons for the lack of a solution based on the analysis of the initial data of the circuit and the mode before solving and in the process of calculating the steady mode, the conditions of applying special algorithms with choosing of the recording form and the method for solving of the equations of steady modes.

A database and a computer program have been developed for calculating the steady-state modes of electrical networks using the DELPHI programming system, excluding random errors in the preparation of initial information about the network diagram.

Errors or incorrectness in specifying the initial information about active and reactive generations and loads in the EN nodes, which are often encountered in practice, are the reasons for the absence of a solution by known methods and programs for calculating steady-state modes. It was determined that when PQ is specified at the nodes of the EN with the EHV OHL the convergence to the admissible solution is not ensured. To obtain a physically realizable solution of the steady mode equations of a of an electric network with an EHV transmission line, a method is proposed based on the input of fictitious PU nodes and consists in the following: calculation of the EN mode by one of the methods, based on the node-by-node solving of the steady mode equations; founding of the fact that it is impossible to obtain a technically feasible solution due to the presence of an EHV transmission line in circuit; transfer of some PQ nodes of the electrical network to fictitious PU (support) nodes; voltage correction of these nodes according to the external iteration algorithm.

As practical criteria for achieving the impossibility of a physically realizable solution of the applied methods for EPS with EHV transmission lines, it is proposed: - determination of the value of the EHV transmission line power P_{ijmax} depending on the length of the overhead line and checking of the condition $P_{ij}>P_{ijmax}$; analysis of voltages and phase angles; founding of the reason for the impossibility of obtaining a technically permissable solution under the conditions $U_i>U_{imax}$ и $\delta_I>\delta_{iprm}$, где $\delta_{iprm}=30\div40^o$, $U_{imax}=1.05U_{in}$. To determine of field application of the methods and programs to achieve to technically feasible solution for calculation steady modes of EN is proposed to found of depedencies of power distribution $P/P_{nat} = f(l)$ from the length of the OHL.

For example, for the area of lengths of SVN overhead transmission lines of $300\leq L_{TL}\leq1200$ km, by numerical modeling of the SME of the test circuits on 500, 750 and 1150 kV, were obtained the P/P_{nat} dependences, approximated by the second power polynomials, for which the SME solution is provided by known programs (Fig. 8).

An algorithm for correcting the voltages of fictitious PU nodes on the feedback formula in the external iterative process is proposed.

For this purpose, a quadratic approximation function $Q_I=f(U_i)$ of the form $Q_i = AU^2+BU+C$ is used for the values of the voltages Ui in the fictitious PU node at three different points. Searching for a solution of the quadratic equation corresponding to $Q_i=0$ is performed. Depending on the EN mode, one of the solutions is technically permissable.

The algorithm for correcting the voltage of a fictitious PU node is in finding a node (PQ or network) with $U_i>U_{imax}$ and $\delta_I>i_{prm}$ as a suspect in ensuring convergence to a physically realizable solution and is converted to a fictitious PU node with specified reactive power limits $|Q_i|<\varepsilon q$.

Numerous calculations have shown that the developed algorithm provides reliable convergence to the values of the sought-for solution of SME, detection of errors in specifying of the EN mode.

The results of the second chapter were reflected by the author in works [11, 15, 16, 17, 22, 30, 32, 54].

The third chapter solves the problem of address distribution of power flows. In market conditions, due to the different cost of electricity from generating stations and other suppliers, the distribution of power and energy flows between market participants is a demanded task. The power supplied to consumers can be generated by various power plants in the EPS, in which the cost of energy is different. Application of address distribution of power flows, provides information on the share of loads in generation; generator contributions to loads; localization of losses for generators and loads.

State assessment data, measurements or CSMPS are input data for the implementation of address distribution of power flows.

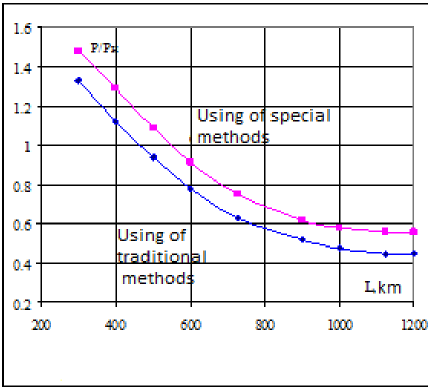

Fig. 8. Areas of applicability of the methods of CSMPS with EHV transmission lines

The matrices A_d and A_b for tracking the paths along and against the flows are equal[3]

$$A_{al} = I + M_{al}^{T} \cdot \mathrm{diag}(P_B) \cdot M_{ag} \cdot \mathrm{diag}(P_{nd})^{-1}$$

$$A_{ag} = I + M_{ag}^{T} \cdot \mathrm{diag}(P_B) \cdot M_{al} \cdot \mathrm{diag}(P_{nd})^{-1}$$

where I - is the identity matrix, M_d and M_b - are matrices for connecting branches at all nodes of the circuit and correspond to the beginning and end of the line, P_{nd} - is the vector of nodal power flows, P_{br} - is the vector of the flows of branches.

Algorithms and a program developed for solving the problem of adressness of active power flows, which allows to determine the share of participation of each station in supplying a specific load and power flows flowing from each generator along the branches of the EN equivalent circuit. An assessment of the address separation of

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[3] Achayuthakan, C. Electricity Tracing in Systems With and Without Circulating Flows: Physical Insights and Mathematical Proofs / C. Achayuthakan, C. J. Dent, J.W. Bialek [et al.] // IEEE transactions on power systems, -2010, vol. 25, N 2, - p. 1078-1087.

active power flows on the IEEE test circuits and Azerbaijan EPS using the developed software carried out.

In fig. 9 shows a test equivalent circuit of the electric network with generator nodes 1 and 2 and load nodes - 3, 4, 5.

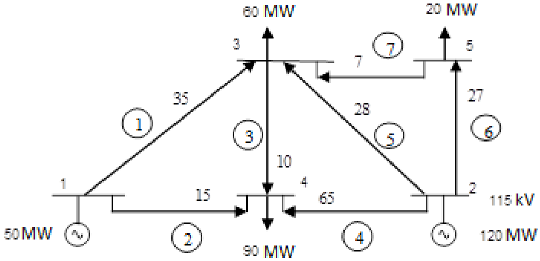

Fig. 9. Scheme for the calculating adressed transmitting of power

The estimation of the address separation of active power flows on the test example by the graph method is carried out.

A study of circulating flows caused by UPFC (FACTS) was carried out on the example of an equivalent heterogeneous section of the EPS of Azerbaijan. An algorithm and a program have been developed for identification of circulating power flows in EPS.

An algorithm and a program for the distribution of active power losses by the marginal method developed. Marginal coefficients can be used as a tool for distributing power and energy losses among market participants.

An algorithm for the application of the Z_y matrix developed both for solving the equations of steady-state modes using the Z-node method, as well as the distribution of losses between market participants. The expression for the components of the total losses of active power, written through the matrix of node resistances Z [2], has the form:

$$\Delta P = \mathrm{Re}\left[\mathrm{diag}(I^*)\cdot Z\cdot I\right]$$

where I* - is the conjugate complex of the nodal current. The algorithm is implemented as a program.

The results of this chapter are reflected in the works [23, 27, 28, 29, 33, 34, 48, 49, 53, 63, 64, 68].

In the fourth chapter, the problems of optimization of EPS modes in modern conditions are investigated. In the problems of operational control of EN modes, it is required to solve problems with a speed corresponding to the speed of the controlled processes.

The control of modes in terms of voltage, reactive power and transformation ratios of transformers is one of the frequently solved problems of electric power systems.

The FACTS devices are included in the model for optimizing of the modes of the electric network in terms of voltage and reactive power by the method of sequential linearization and linear programming.

The mathematical model of the problem of optimization of the electrical network in terms of voltage, reactive power and transformation ratios of transformers taking into account FACTS devices can be represented as[4]:

$$\text{Minimization} \qquad F(X,Y),$$

$$\text{at restrictions} \qquad W(X,Y)=0$$

$$X_{min} < X < X_{max} \qquad U_{smin} \leq U_s \leq U_{smax} \quad ,$$

$$Y_{min} < Y < Y_{max}\,, \quad -\frac{\pi}{2} \leq \gamma_s \leq \frac{\pi}{2}$$

where F(X,Y) - total losses of active power in the electrical network X - vector of unregulated variables (modules and phases of voltage, reactive power sources, module of voltage of longitudinal voltage source FACTS); Y - vector of regulatled variables; U_s - module of voltage of the longitudinal voltage source FACTS; γ_s - phase angle of the i-th longitudinal voltage source FACTS.

The mathematical model of optimization of the EPS mode by voltage and reactive power belongs to the class of nonlinear programming problems, which are characterized by high

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[4] Idelchik, V.I. Raschety i nastroyki elektricheskikh sistem / V.I. Idel'chik. - Moskva: Energoatomizdat, - 1988. – 288 c.

dimensionality, nonlinearity of the objective function and equations-constraints on the dependent variables, poor filling of the matrix of the coefficients of the equations, and large time spending for its solving.

The efficiency of solving the optimization problem can be increased by using an iterative procedure of sequential linearization of the objective function and constraints using linear programming methods.

Optimization of the EPS mode by U, Q, K_T taking into account FACTS devices by the method of sequential linearization is reduced to the following.

1. CSMPS of initial approximation is carried out;
2. The linearization of the SME and the objective function is performed;
3. The problem of LP in deviations is formed and solved;
4. The next approximation is determined and a convertion from deviations to the absolute values of the variables is made;
5. Iterative repetition of the MAP optimization process continues until a predetermined accuracy is achieved with respect to the difference in the values of the objective function in last two iterations.

By expanding the SME of the electric power system in a Taylor series in the vicinity of the planned mode Y_0, we obtain linearized equations that are valid for a sufficiently small $\Delta Y = Y - Y_0$

$$\left[\frac{\partial W}{\partial X}\right]\Delta X = -\left[\frac{\partial W}{\partial Y}\right]\Delta Y,$$

where $\partial W/\partial X$ is a matrix of derivatives of power disbalances with respect to dependent variables, $\partial W/\partial Y$ is a matrix of derivatives of power disbalances with respect to regulated variables, $\Delta X = X - X_0$ is a vector of corrections to dependent variables.

In this case, the linearized equations of the steady-state mode are represented in the form

$$\Delta X = S_{xy}\Delta Y,$$

The objective function is linearized by expanding the total active power losses in a Taylor series in the vicinity of the mode that planned

$$F = F(X_0, Y_0) + \frac{\partial F}{\partial Y}\Delta Y + \frac{\partial F}{\partial X}\Delta X = F(X_0, Y_0) + S_{FY}\Delta Y$$

where $F(X_0,Y_0)$ is the objective function component at the linearization point.

The objective function is represented in the transformed form

$$\Delta(\Delta P_{total}) = c_U \cdot \Delta U + c_Q \cdot \Delta Q + c_{Ti} \cdot \Delta K_{Td} + c_{Ti} \cdot \Delta K_{Tq};$$

where c_u, c_Q, c_{kt1}, c_{kt2} - are coefficients of linearized expressions for total losses.

To optimize the mode in terms of active power, a program developed in the Delphi programming system.

Traditionally, at economy load distribution, the cost function for each generator is approximately represented as a simple quadratic function:

$$\grave{E} = \sum_i \left(a_i + b_i P_i + c_i P_i^2 \right)$$

where A - total costs; a_i, b_i, c_i - the coefficients of the costs of the generator i; P_i - is the generation power of generator i.

The classical approaches to the implementation of this problem are unstable. From this point of view, a promising direction is associated with the applying of ANN methods.

An algorithm and a program using the Hopfield ANN for the economic distribution of the load between power plants developed. The dynamics of neurons is defined as:

$$\frac{dU_i}{dt} = \sum_j T_{ij} V_j + I_i$$

where $V_i = g_i(U_i)$ - output of neuron i; $g_i(U_i) = \frac{1}{1 + e^{(-U_i/u_0)}}$ - function input-output of neuron i; uo - coefficient that determines the form of the sigmoid function.

The energy function of the Hopfield network is defined as [5]:

$$E = -\frac{1}{2}\sum_{j\neq i}\sum T_{ij}V_iV_j - \sum I_iV_i + \sum \theta_i V_i$$

The change in energy in accordance with the change in the state of neuron i by ΔV_i is equal to:

$$\Delta E = -\left[\sum_{j\neq i} T_{ij}V_j + I_i - \theta_i\right]\Delta V_i$$

where ΔV_i - the change in the output of neuron i.

The synaptic force and the external input of neuron i in the Hopfield neural network are represented as:

$$T_{ii} = -A - Bc_i; \qquad T_{ij} = -A; I_i = A(P_{total} + \Delta P) - \frac{Bb_i}{2}$$

The difference transient model used in calculations for the Hopfield neural network has the form:

$$U_i(k) - U_i(k-1) = \sum_j T_{ij}V_j(k) + I_i; V_j(k+1) = g_i[U_i(k)].$$

To calculate losses in the Azerbaijan EPS with a total load 3400 MW of the power system, the dependence of active power losses on the generation of power by power plants was used in the form of a verbal description of an artificial neural network, obtained on the basis of the results of multivariative calculations of the SM. Table 4 presented the actual and optimal values of the generation of active powers of TPP.

Table 4

Actual and optimal power generated by TPP

Name	Actual values of P_{gen},	Fuel consump tion, ton	Optimal values of P_{gen} according to the method, MW	Fuel consum ption,	Saving fuel, ton per

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[5] Park, J. H., Kim, Y. S., Eom, I. K., Lee, K. Y. Economic load dispatch for piecewise quadratic cost function using Hopfield neural network // IEEE Trans. Power Systems, -1993. vol. 8, no. 3, -p. 1030–1038.

	MW	per hour	Hop field	Numerical	ton per hour	hour
AzTPP	1925	606.904	1895.7	1897	598.88	8.02
Shirvan	490	179.47	331.5	332.3	129.59	49.88
Shimal	360	83.44	399	400	91.85	-8.41
BakTEC-1	67	14.38	109	110	22.54	-8.16
Module	262	71.91	362	365	97.21	-25. 30
Total	3104	956.104	3097.2	3104	940.07	16.03

A methodics and an algorithm for optimizing the EN mode developed based on obtaining regression equations for flows and power losses from parameters controlled by FACTS.

It was foun that the optimal distribution of active power between the power plants of the Azerbaijan EPS using market mechanisms allows to obtain an economic effect by reducing fuel consumption, estimated at 16.3*5000 = 81,500 tons per year. It was found that the optimal placement of the installation of FACTS devices (STC, UPFC) on separate sections of 220-500 kV of the Azerenerji EN leads to a decrease in active power losses of more than 4-7 MW and an increase in the operation efficiency of the EPS Azerbaijan.

The analysis of the heterogeneity of the EN circuit 220-500 kV of "Azerenerji" for the installation of the UPFC is carried out.

To modeling of the influence of the branches on the ES heterogeneity, the expression was used $|\gamma|_i = \left[\sqrt{\sum_{j=1}^{m}\gamma_{ij}^2}\right]$, $i = 1,..n$, where $\gamma = M^T \cdot x \cdot r^{-1} - x_B r_B^{-1} \cdot M^T$; $z_B = r_B + jx_B$ - the diagonal resistance matrix of the EN branches, MT - is the transposed matrix of the connections of the branches at the nodes[6].

The sensitivity of active power losses in longitudinal reactance is determined as follows.

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[6] Lezhnyuk, P.D., Kulik, V.V., Obolonskiy, D.I. Modelirovaniye i kompensatsiya vliyaniya neodnorodnosti elektricheskikh setey na ekonomichnost' ikh rezhima // - Moskva: Elektrichestvo - 2007. № 11, - c. 2-8.

$$b_{ij} = \frac{\partial P_L}{\partial X_{ij}} = -2\left[V_i^2 + V_j^2 - 2V_i V_j \cos\delta_{ij}\right] \cdot G_{ij} B_{ij}$$

The diagram of the accelerated indicator of static stability in voltage for the branches of the 24-nodes circuit of Azerenerji is shown in Fig. 10.

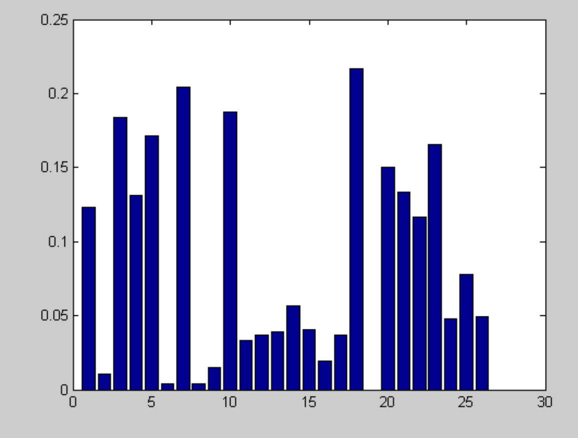

Fig. 10. Sensitivity of branches of a 24-nodes circuit

The results of the fourth chapter are reflected in the works [1, 2, 12, 13, 37,38, 50, 52, 53, 55].

The fifth chapter presents the results of forecasting and measuring electricity losses based on regression models. Traditionally, the calculations of losses in each report period are based on a series of steady-state modes on a computer according to the circuit and mode parameters of the network. Given calculations are associated with high dimensionality, information problems and calculation time. Operational control requires high-speed control and forecasting algorithms in power supply systems.

To forecasting of the load losses of active power, a polynomial model of the form

$$\Delta P(x_1, \ldots, x_k) = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{i,j} x_i x_{ij} + \sum_{i=1}^{k} b_{ii} x_i^2,$$

where ΔP - power losses; x_i and x_j - independent variables of the regression equation; b_0, b_i, b_{ij}, b_{ii} - coefficients of the regression equation; k - is the number of factors.

A software and computational complex has been developed to automate the procedure for many experiments of the MPE and CSMPS. The program automates: compiling an experiment planning matrix, carrying out a series of calculations by the CSMPS, processing of the obtained results, searching for regression coefficients, and checking the forecasting error. This program was used to forecast active power losses in the EN voltages of 110-500 kV of Azerenerji JSC from the active capacities of power plants, voltages and reactive power of power plants. The advantage of obtaining equivalent characteristics of the electrical network in power losses is elimination of iterative calculations. Table 5 shows the coefficients of the power loss regression equation in the form of a full quadratic model, obtained for the Azerenerji circuit.

A software module developed for planning a set of experiments by simulation of losses for obtaining coefficients of regression equations by LSM, which consists of subroutines: input and output of information, generation of random numbers and processing of experimental results, formation of normal LSM equations and solving a system of linear equations by the Gaussian method, evaluating the significance of the coefficients, and checking the adequacy of the equation as a whole.

In this case, the standard deviation was 0.78%, and the maximum error was 2.12%.

Table 5

Quadratic Regression Coefficients ($B_0 = 49.543$)

№	Name of node	Factor type	Coefficients	
			Linear	Non-linear
1	Sumg-TPP	P	1.3173	1.329
2	Shimal TPP	P	4.2234	6.767
3	BAKTPP-1	P	-0.4704	0.360
4	SHIR220	P	1.6042	1.382
5	Sum-P_n	P	12.2802	19.876
6	Sumg -TPP	Q	1.6797	0.662

The predicting possibility of power losses in EN of power systems by applying of ANN also investigated.

From a comparative analysis of methods for obtaining regression dependences for power losses, it follows that the MPE is advantageous with the dimension of the problem up to 10 factors, and the LSM is more than 10 factors with almost the same accuracy of obtaining the result. At the same time, LSM significantly saves time. ANN has an advantage when high accuracy of the result is required.

A method is proposed for determining the variable losses of the electronic equipment by imitation of the schedules of electrical loads by duration. Load schedules over duration for various values of Tmax can be represented as a continuous random variable submissing to the beta distribution law[7]:

$$F(x,\gamma,\eta)=\begin{cases} 0 & x<0, \\ \dfrac{\tilde{A}(\gamma+\eta)}{\tilde{A}(\gamma)\tilde{A}(\eta)}\displaystyle\int_0^x t^{\gamma-1}(1-t)^{\eta-1}, & 0\le x\le 1, \mapsto \\ 1, & x>1, \end{cases}$$

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[7] Klebanov, L.D. Voprosy metodiki opredeleniya i snizheniya poter' elektricheskoy energii v setyakh / L.D. Klebanov. - Leningrad: Izd-vo LGU, -1973. - 72 s.

where Γ – Gamma function, $\Gamma(\eta) = \int_0^\infty x^{\eta-1} \cdot e^{-x} dx$, γ and η - are the form parameters of the distribution functions.

We consider obtaining empirical dependencies for k^2_f by approximating the load graphs by exponential dependences of the form $\mathbf{I} = \mathbf{I}_{\min} + (\mathbf{I}_{\max} - \mathbf{I}_{\min}) \cdot \mathbf{e}^{-(\alpha_2 \mathbf{t})^{\rho}}$ Here α and ρ are the scale parameters determining as a result of the approximation.

The developed technique for determining variable losses by simulation allows to increase the accuracy of modeling the form factor and has advantages over the known programs in simplicity and time spending. The dependencies of the intervals of variation of k^2_f, obtained by simulating of the load graphs on k_s, k_{min} and k_{tmin} are shown in Fig. 11.

The possibility of measuring active power losses by measuring active powers at the ends of the OHL applying of an automated system using specialized measurement system is shown.

In fig. 12 shows a system for measuring mode parameters, consisting of measuring system at the beginning of the line "2nd Absheron" 500 kV at the substation "Azerbaijan TPP" 500/330 kV and measuring system at the end of the line at the substation "Absheron" 500/330/220 kV.

Graphs of active and reactive powers and voltages at the beginning and end of 500 kV OHL for day with an averaging time of 5 minutes are shown in Fig. 13.

It is proposed to promptly clarify the active power losses on corona and on heating the wires and, accordingly, the active resistance and conductivity, as well as the capacitance during the operation of the OHL by tracking the parameters of mode of the line.

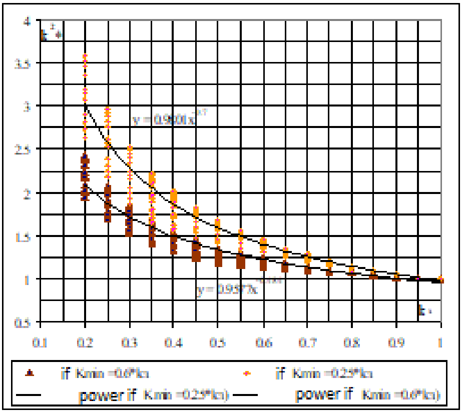

Fig. 11. Limits of $k^2{}_f$ change

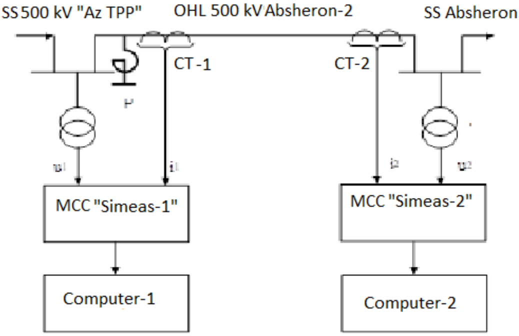

Fig. 12. Measuring scheme of the parameters of the mode of the 500 kV OHL

A program developed for calculating systematic errors of MCC active power and EE in a high-voltage electrical network based on the full parameters of CT and VT. The program can be used both for operational calculation of MC errors at the rate of the measurement process, and for obtaining characteristics in an analytical form.

The allocated losses of the 500 kV OHL are shown in Fig. 14.

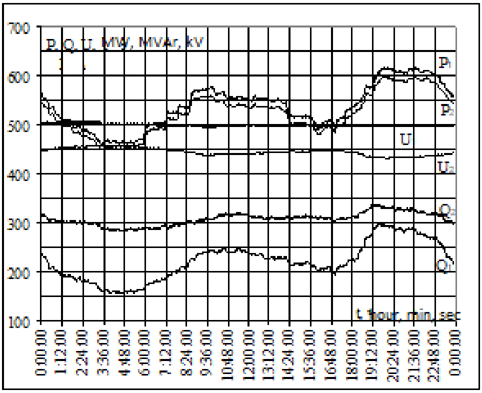

Fig.13. Measurements of operating parameters of 500 kV OHL

The results of the fifth chapter are reflected in the works [3, 5, 6-10, 18-20, 24-26, 35, 39-41, 43-44].

In the sixth chapter, a mathematical model of the transmission line is developed, based on synchronized vector measurements (SVM) and corresponding their accuracy.

SCADA complexes receive and process teleinformation once a second, without synchronizing measurements in astronomical time. With the creation of satellite communication systems, new measuring equipment - PMU (phasor measurement units) appeared. The vector of SCADA - measurements used in the traditional statement of the EPS OS has the form: $\bar{y} = \{P_i, Q_i, P_{ij} \cdot Q_{ij}, U_i, I_i, I_{ij}\}$. Unlike SCADA, PMU measurements are $Y = [U_i, I_{ij}, \delta_i, \varphi_{ij}]$.

Regarding with the increase in the measurement accuracy, it becomes relevant to choose a mathematical model of OHL for assessment of the state of the OHL, corresponding to the accuracy of synchronized vector measurements.

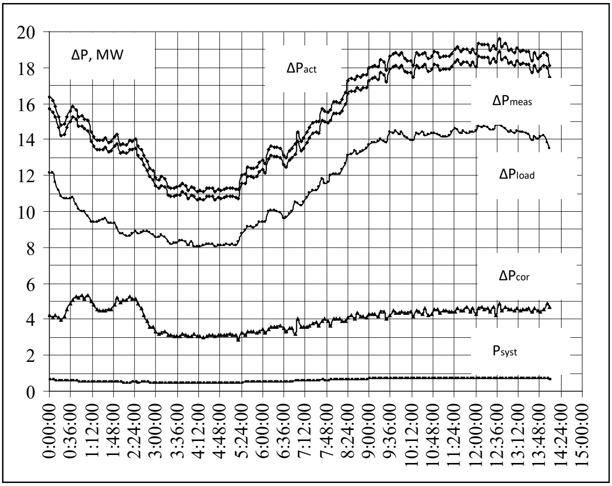

Fig. 14. Verified losses of 500 kV OHL

The method to increase of the accuracy of modeling the mode of SHV transmission lines proposed in this chapter is based on representing the OHL in the form of a π-form diagram of TL sections, modeling power losses to the corona using dependencies on the voltage of ρ-th degree, in determination of the reactive effect of the corona, presenting power losses to the corona and an additional reactive load at the ends of the transmission line section and sequential calculation of the voltage at the beginning of each section according to the data at its end, the calculated equivalent circuit of the section of which is shown in Fig. 15.

The mathematical model for calculating the mode of a line section consists of the following stages:

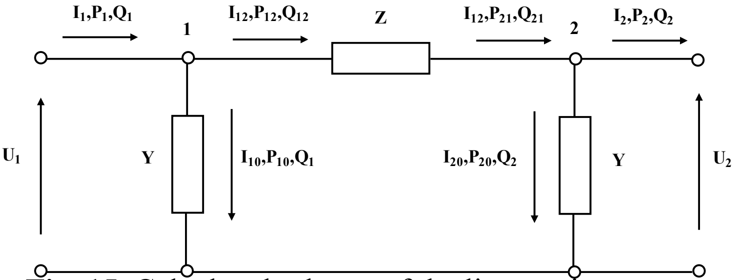

Fig. 15. Calculated scheme of the line section

Load current at the end of the OHL

$$I_{\text{наг}} = \frac{S_{\text{наг}}}{\sqrt{3} \cdot U}, \quad I_2 = I_{\text{наг}}$$

Current in line

$$I_{12} = I_2 + U_2 \cdot Y, \qquad I_{21} = I_1 - U_1 \cdot Y$$

Voltage at the beginning of OHL

$$\Delta U_{12} = I_{12} \cdot Z_{12}, \qquad \overline{U}_1 = \overline{U}_2 + \Delta\overline{U}_{12}$$

Here, Z - is the resistance of the section, $Z_0 = r_0 + jx_0$; Y_0 — specific line conductivity, $Y_0 = g_0 + jb_0$.

The parameters of the equivalent circuit based on measuring the complexes of current and voltage at the ends of the line are determined from the equations of the OHL describing the mode.

These equations are obtained by representing losses by conductivity

$$g_0 = \frac{\Delta P_{k0}}{U^2}$$

where $\Delta P_{к0}$ - specific corona losses of OHL, corresponding to the nominal line voltage Unom.

Specific corona losses can be represented as a voltage dependency of the form

$$\Delta P_k = \Delta P_{k0} \cdot \left(\frac{U_k}{U_{nom}} \right)^{\rho}$$

where U_k - is the actual voltage at node k, ρ - an exponent.

At the same time, the power loss can be defined as the loss in the uniformly distributed conductivity of the OHL.

The real characteristic of the corona losses of the PTL can be represented as a dependence on the voltage of the form

$$\Delta P_k = 3 \cdot g_0 \cdot \int_0^L U_l^\rho dl$$

where L - is the length of the OHL, km.

The additional capacitance in equations of a distributed line is determined by the known characteristic of power losses on corona and the shift angle of the first harmonic of the corona current relative to the voltage:

$$\Delta C = \frac{\Delta P_k}{\omega \cdot U^2} \cdot \mathrm{tg}\,\psi$$

where ω - the angular frequency; U - the line voltage; ψ - the phase angle of the shift of the first harmonic of the corona current relative of the voltage.

On the basis of the proposed technique, a program for modeling the PTL mode has been developed. The algorithm for solving the problem of assessing the state of PTL using data from the SVM and taking into account of the characteristics losses from voltage is reduce to following:

1. Setting the initial data on EHV TL, characteristics of corona losses and the degree index ρ of voltage for a group of weather conditions.
2. Modeling of corona power losses using dependences from voltage accordind to the mode data at the ends of the section and representing them as an additional load at the ends of line.
3. Modeling the reactive effect of the corona of a line section as additional reactive conductivity and representing it in line equations in the form total conductivity.
4. Calculation of the EHV transmission line section mode on the equations of line with distributed parameters.

5. Calculation of the mode of the EHV TL section on the equations of the π-form diagram and Newton's method.

6. Estimation of the state by linear and nonlinear methods.

To modeling of the EHV TL mode on the basis of PMU measurements and the effect of additional capacitance on the calculating results of the steady-state modes of electrical networks, calculations were carried out for a 500 kV OHL with a phase construction of 3xAC-330/43, r0 = 0.029 Ohm/km, x_0 = 0.299 Ohm/km, $b_0 = 3.74*10^{-6}$ S/km. The length of the line is 350 km.

The calculations were carried out when setting of the index degree of the characteristic of losses from voltage ρ = 4, the temperature of the wire 20°C and the temperature of the wire -10°C with the exponent of the characteristic of losses from voltage ρ = 2.4.

Table 6 shows the results of calculating the OHL for the transmission mode at the end of the line U_2 = 490 kV and S_2 = 900 + j50 MVA with specific corona losses of 4 W/m, depending on the length of the links, obtained from the line equations in the form of the power balance at the nodes and by solving with Newton's method.

The last row of the table presents the results of calculating the OHL mode according to equations with distributed parameters taken as reference.

PMU measurements are modeled by noise reduction of steady state calculation results. The measurement accuracy for PMU is accepted: for current and voltage - 0.3%, for angle - 0.10%.

Table 6

Calculation results of the 500 kV OHL mode according to π-form OHL scheme

Representation of OHL 350 km by sections		U_{int}	Δ_{int}	I_{int}	φ_{int}
Number	Length, km	kV	Rad.	kA	rad
1	350	523.2937	0.3810	1.7944	-0.3040
2	175	521.5721	0.3755	1.7976	-0.3066
3	116.67	521.2644	0.3746	1.7982	-0.3070
4	87.5	521.1575	0.3742	1.7984	-0.3072
5	70	521.1081	0.3740	1.7984	-0.3073
7	50	521.0652	0.3739	1.7985	-0.3073
	On ELL	521.0206	0.3737		

In fig. 16 shows the results of nonlinear estimation of the state depending on the length of the line sections at specific power losses on corona corresponding to the group of rime 100 W/m and the degree index of characteristic from voltage $\rho = 2$.

The results for SE show that the shorter the length of the OHL links, the lower the SE RMS and the higher of the model accuracy. The methodological error of the OHL model grows with an increasing of corona losses level. Under good weather conditions, the methodical error according to the π-form circuit of the OHL reaches up to 0.014%. Under bad weather conditions (rain, frost), the modeling error according to the π-form OHL circuit increases and σ reaches 0.3% and more. Therefore, to improve the modeling accuracy of the π-form OHL circuit and to compatible it with the PMU data accuracy, it becomes necessary to use the π-form circuit OHL with shorter chain link lengths.

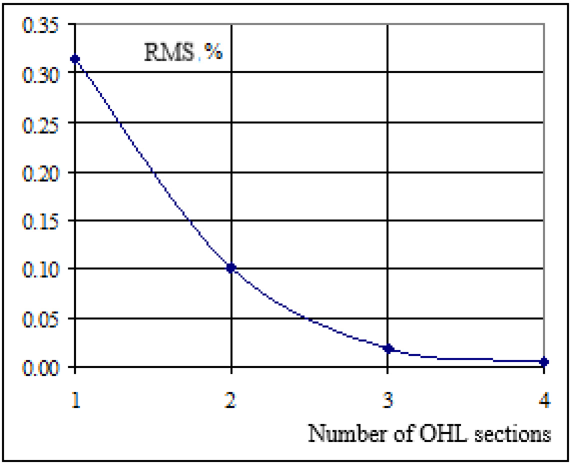

Fig. 16. Dependence of voltage RMS deviation in a percentage on the number of OHL sections

The dependences of the methodological errors of calculation of 500 kV TL with a length of 350 km according to the π-form equivalent circuit at $\Delta P_{k0} = 100$ W/m, $\rho = 4$, $\Delta C = 10\%$ are shown in Fig. 17.

Below are the results of calculating the OHL (V-form circuit) with 2 nodes according to the end data - accurate data on equations of the long line and based on the calculation by Newton's method.

The results of linear estimation of the state depending on the length of the line sections at specific power losses on corona corresponding to the good weather group of 4 W/m and the degree index of characteristic from voltage $\rho = 2$ are shown in Fig. 18.

On the Newton-Raphson method:

$$\mathrm{VecMN} := \begin{pmatrix} \mathrm{UnacMN} \\ \mathrm{User2MN} \\ \mathrm{UkonMN} \\ \mathrm{I12MN} \\ -\mathrm{I21MN} \\ \mathrm{I23MN} \\ -\mathrm{I32MN} \end{pmatrix} = \begin{pmatrix} 521.02058 \\ 496.29613 - 92.38887i \\ 454.90177 - 179.89807i \\ 1.7954 + 0.128i \\ -1.7637 - 0.4607i \\ 1.7637 + 0.4607i \\ -1.6733 - 0.7716i \end{pmatrix}.$$

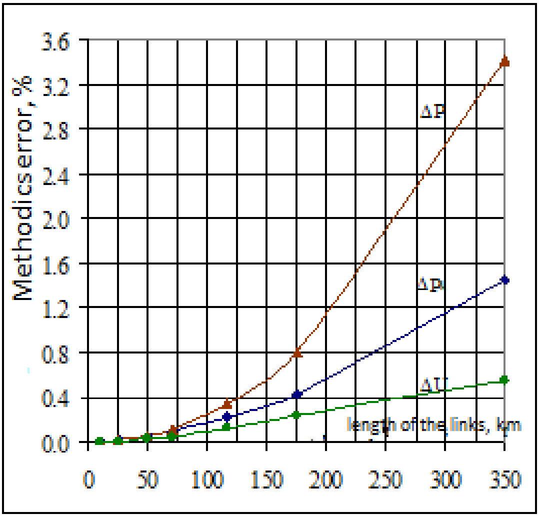

Fig. 17. Dependences of errors on the length of the links

On long line equations:

$$\mathrm{VecEt} := \begin{pmatrix} \mathrm{UnacEt} \\ \mathrm{User2Et} \\ \mathrm{UkonEt} \\ \mathrm{I12Et} \\ -\mathrm{I21Et} \\ \mathrm{I23NEt} \\ -\mathrm{I32KEt} \end{pmatrix} = \begin{pmatrix} 521.02058 \\ 496.9188 - 91.8778i \\ 456.17116 - 178.90745i \\ 1.79465 + 0.1193i \\ -1.76297 - 0.45323i \\ 1.76297 + 0.45323i \\ -1.67267 - 0.76562i \end{pmatrix}.$$

After assessing of the state:

$$\mathrm{OsenkaVekSost} = \begin{pmatrix} 521.0591 + 0.0039i \\ 508.5433 - 46.1204i \\ 491.7732 - 90.9249i \\ 481.0698 - 136.8879i \\ 456.0588 - 178.9172i \end{pmatrix}.$$

The results of linear estimation of the state (LES) when dividing the OHL into 2 sections, the obtained RMS has significantly decreased (from 1.29% to 0.244%) and this confirms the effectiveness of LES.

The results of the study of the errors of simplified models using the example of EHV TL show that the methodological errors of the known simplified models of steady-state modes in comparison with the equations of the OHL with distributed parameters do not provide the corresponding SVM accuracy.

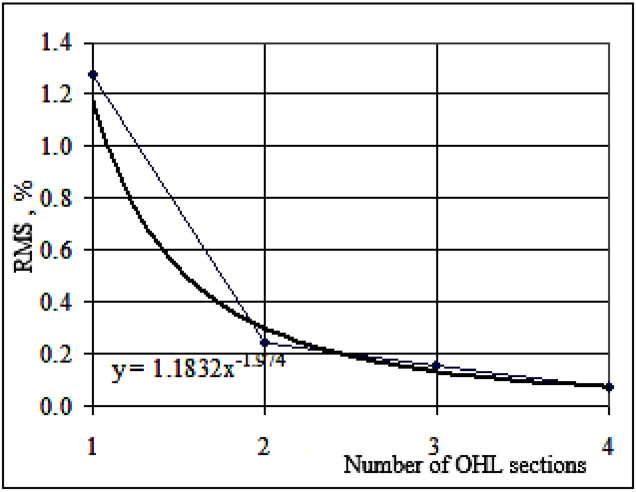

Fig. 18. Dependence of voltage rms deviation in percent on the number of OHL sections

In the Kipnis-Shamir relinearization method, the measurement equations are formated by using the rectangular coordinates of the bus voltages. With this formulation, nonlinear measurement equations become quadratic voltage polynomials. Then the method uses two transformations of the original system into a system of higher dimension to solve the quadratic variables in a non-iterative way[8].

The measurement equations have following form:

- - measurement of voltage values

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[8] Jiang, X. T. Power system state estimation using a direct non-iterative method / X. T. Jiang; J. H. Chow; B. Fardanesh. [et al.] // International Journal of Electrical Power & Energy Systems, vol. 73, -2015, -p. 361-368.

$$U_i^2 = U_{iR}^2 + U_{Ii}^2; \qquad U_j^2 = U_{jR}^2 + U_{ji}^2;$$

where U_i and U_j are the voltage values of nodes *i* and *j*.

- equations of active and reactive power flows

$$P_{ij} = g_{ij}\left(U_{iR}^2 + U_{Ii}^2 - U_{iR}U_{jR} - U_{iI}U_{jI}\right) + b_{ij}\left(U_{iI}U_{jR} - U_{iR}U_{jI}\right);$$

$$Q_{ij} = b_{ij}\left(U_{iR}^2 + U_{Ii}^2 - U_{iR}U_{jR} - U_{iI}U_{jI}\right) + g_{ij}\left(U_{iR}U_{jI} - U_{iI}U_{jR}\right) + b_s U_i^2;$$

$$g_{ij} = \frac{R_{ij}}{Z_{ij}^2},\ b_{ij} = \frac{X_{ij}}{Z_{ij}^2}; \qquad Z_{ij}^2 = R_{ij}^2 + X_{ij}^2;$$

where i - node of sending of active power, j - node of receiving active power; R_{ij}, X_{ij}, b_s - line resistance, reactance and conductivity to ground, respectively.

The nodal power equations are composed as follows:

$$P_i = \sum P_{ij} + G_i U_i^2, \qquad Q_i = \sum Q_{ij} + B_i U_i^2.$$

where j - the set of nodes connected to node *i*.

So as these equations are linear with respect to the quadratic voltage terms (U_{iR}^2; U_{iI}^2; U_{iR};U_{jR} etc.) they can be represented in matrix form

$$A_\xi \xi = C$$

where C - the vector of measured values, ξ - the vector of quadratic voltage variables, and Aξ - the matrix of coefficients for ξ.

Variables are replaced, and the system $A_\xi \xi = C$ takes the form:

$$\begin{bmatrix} A\ B \end{bmatrix} \begin{bmatrix} Y \\ Z \end{bmatrix} = C,$$

where A - contains linearly independent columns of Aξ, and B contains the remaining columns of Aξ, Y - a vector of elements ξ corresponding to A, and Z is a vector of elements corresponding to B.

The above system in its expanded form is represented as:

$$\begin{bmatrix} y_1 \ldots\ldots y_{N_y}\, z_1 \ldots\ldots z_{N_z} \end{bmatrix}^T = E \cdot \begin{bmatrix} 1\ \ z_1 \ldots. z_{N_z} \end{bmatrix}^T;$$

$$E = \begin{bmatrix} d & 0.....0 \\ D & I \end{bmatrix}^T.$$

The simulation was carried out on a 500 kV TL with 350 km long. Measurements of the flow of active (P) and reactive (Q) power from node 1 to node 2 are obtained from four measurement equations (Fig. 15).

OHL parameters in relative units: R = 0.0046; X = 0.04186; g = 0.014; b = 3.2. The measurements are equal: U_1 = 520.06 kV; U_2 = 490 kV; P_{12} = 935.18 MW; Q_{12} = 80.07 MVAr.

The results of calculating of the PTL steady-state mode by nodes and branches are as follows: U_1=1.042; U_2=0.973; $\delta_1=0^o$; $\delta_2=-22.64^o$; P_{1gen}=935.18 MW; Q_{1gen}=80.070 MVAr; P_{1load}= 0 MVt; Q_{1load}=0 MVAr; P_{2gen}=0 MVt; Q_{2gen}=0 MVAr; P_{2load}=900 MVt; Q_{2load}=50 MVAr; P_{12}=935.18 MVt; P_{21}=900 MW; Q_{12}=80.07 MVAr; Q_{21}=50 Var. Load power losses are ΔP=35.184 MW, ΔQ=62.76 MVar.

The results of this chapter are reflected in the works [56, 57, 58, 65, 66, 69].

Main results of work

1. A methodology, algorithm and software for analysis, planning and control of steady-state modes of EPS, taking into account FACTS devices, have been developed.

2. The stages of formalization of the problem on CSMPS with the use of ANN have been worked out, a methodology and software for CSMPS by applying of ANN have been developed.

3. The problems of the automated search for the solution of the SME EN on the basis of the analysis of the initial data were set and solved, which make it possible to increase of the reliability of obtaining the solution. Algorithms for finding a solution by formalizing individual stages are proposed: diagnostics of the reasons for non-convergence or absence of a solution based on data analysis, a circuit and a mode, conditions for the applying of special algorithms with a choice of the form of the SM equations and the solution method.

4. The issues of optimizing the EPS mode by active power on the wholesale market have been worked out, a program has been developed based on the coordinate descent method, taking into account the restrictions in the form of inequalities.

5. An algorithm and a program by applying of an artificial neural network of Hopfield for the economic distribution of the load between power plants are developed. It has found that the optimal distribution of active power between the power plants of the Azerbaijan EPS using market mechanisms makes it possible to get an economic effect by reducing fuel consumption, estimated at 16.3*5000 = 81,500 tons per year.

6. The problem of determining the energy of variable losses and evaluating the intervals of changes in losses by imitating of the graphs of electrical loads in the form of an exponential function have been set and solved.

7. Methods, algorithms and programs for constructing regression dependencies based on the results of simulation and by applying of statistical methods for planning an experiment, the least squares method and artificial neural networks have been developed.

8. An algorithm based on the analysis of sensitivity by the Jacobi and Z-matrix and generalized EN indicators has been developed, implemented in the form of software for preliminary assessment of weak points and of EN heterogeneity degree in order to select of the location of FACTS devices. A technique and an algorithm for optimizing the EN mode have been developed based on obtaining regression equations for flows and power losses from parameters controlled by FACTS.

9. Requirements for the systems for the operational assessment of active power losses based on the current parameters of the mode at the ends of the EHV OHL have been formulated. Experimental studies were carried out to determining of corona losses by measuring the mode parameters at the ends of 500 kV OHL using a specialized measurement system.

10. Experimental studies were carried out to assess the effect of an abruptly load in the deterioration of the EE quality indicators at a high-voltage substation, and a violation of the PQEE, in particular, of the flicker dose, was found. The applying of high-speed FACTS devices allows solving of the problem of level reducing of voltage fluctuations.

11. Complexes of programs for calculating EE losses have been developed, the results of which implemented at the leading enterprises of Azerenerji JSC. The obtained solutions make it possible to improve the EE metering system, to increase the efficiency of work, to plan measures to improve the efficiency of the EPS operation. Optimal placement of FACTS devices on separate sections of 220-500 kV of the EPS of Azerbaijan can lead to a decrease in active power losses by more than 4.37÷7.57 MW and an increase in operating efficiency.

12. A method and an algorithm for evaluating the state of OHL, based on the SVM, have been proposed. It has found that the use of the algorithm for linear estimation of the state of the EHV TL based on the measurements of the SVM leads to a significant decrease in the RMS.

13. A method that allows solving the problem of state estimation in a non-iterative way has been developed.

The main content of the dissertation is published in the following publications:

1. Баламетов, А.Б., Мусаханова, Г.С., Халилов, Э.Д. Исследование решения задачи оптимизации режимов электрических сетей по напряжению и реактивной мощности методом последовательной линеаризации и линейного программирования // – Москва: - Электричество, - 2003. №3, -с. 17-26.
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7. Баламетов, А.Б. Об оценке потерь энергии при вероятностном представлении графиков электрических нагрузок / А.Б. Баламетов, Х.Т. Алиев, Э.Д. Халилов [и др.] // -Баку: Проблемы энергетики, «ЭЛМ», - 2007, №1, - с. 27-35.

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