Georgian Technical University

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Optimization and Management of the Modes of Distribution Electrical Chains

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ABSTRACT

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General description of the work

Problem urgency. At present, a new social system is being formed in Georgia. A new system of political and economic relations, which should create principally new conditions for independent existence and sustainable development of Georgia, is being introduced to the country.

During this process, the establishment of efficient conditions for transformation and development of the energy sector is of special importance. The energy sector should provide the basis for stable functioning and sustainable development of the country. At the same time, on the background of global political and economic processes taking place all over the world the power sector of Georgia is able to get successfully engaged in power production, transportation and consumption in the region and to take part in the process of establishing economic conditions for economic integration and political stability of the whole region.

Under modern conditions of development of the market economy in the country, finding autonomous solutions to a number of technical tasks for various local distribution electrical chains is urgent. At the same time, independent departmental sub-units in the electrical chain impede the practical realization of the idea of simultaneous functioning of voltage chains of all steps of the system. Such state of affairs to a certain degree forces to reject classical methods of full-scale realization of the principle of system approach and makes us use different equivalency methods given we have initial information at hand. Such an approach will enable us to easily overcome the difficulties with gaining thorough and sufficient data about the configuration, electric parameters of the elements and loads in customer nodes for the whole network. At the same time, rejection of the system approach will result in a significant error and the solution to the set task will be similarly erroneous resulting in an also erroneous technical-economic effect.

Such is the problem of optimal compensation of the reactive load in the given regional distribution networks, which, without any exaggeration, may be described as a system task.

The principle of equivalence enabling us to solve the set task in isolation from the rest of the network and to approximate the task results to the results of the task solution gained through the application of the principle of system approach, is an extremely urgent issue for successful functioning of the energy distribution companies in conditions of the present market economy.

The aim of the work is, in conditions of relatively easily available and minimally necessary amount of information, to get a simplified mathematical model with a significantly reduced dimension for the task of optimal compensation of the reactive load in the regional

distribution network under review. The model should enable us get a sufficiently accurate result for engineering calculations. Following this, the work analyzes:

- Hierarchical structure of the electric system and the degree of interaction of the levels of the given structure;
- Qualitative and quantitative ratios of internal and mutual resistances of the network nodes;
- Constituents of relative increment of the effective output losses against the network nodes and the degree of their influence on the result of the set task;
- Load shifting from the network nodes (network equivalenting) and its influence on the task results;
- Deep analysis of the equations set gained through the principle of system approach to the problem and the possibility of reducing its dimension.

Analysis of these and many other issues has enabled us to successfully solve the problem set in the dissertation.

Method of theoretical study, by considering the clearly established hierarchical structure of electric system, aiming at reducing the dimension of the mathematical model of the set task, is based on isolating the principal kernel out of equations set corresponding to the given mathematical model, which characterizes the concrete regional network and on fixing the coefficient of influence of the rest of the electric system on it.

The results of the set task gained through the application of the simplified mathematical model resultant of the theoretical study, with the purpose of examining their accuracy were compared to the ones gained through thorough application of the principle of the systematic approach. The results of the comparison proved the correctness of the mathematical model referred to in the dissertation and the purposefulness of their practical application.

Scientific novelty. Unlike the existing scientific-technical literary sources, the present dissertation for the first time has featured and found positive solution to the issue of clear secularization of the essential and less essential initial information against the set task, as well as the issue of fixing their interaction factor.

Based on the coefficient of optimal compensation of reactive load in the customer nodes, there was a new simplified mathematical model gained, by whose application in conditions of minimal amount of the initial information gaining a sufficiently accurate result for engineering calculations becomes possible. The necessity for gathering hardly accessible, less probable or less essential information for the regional network under review is in fact impossible.

Practical value. The work shows a calculation formula enabling to set the equations set of the task of optimal compensation of the reactive load for the regional distribution network, where the rest section of the electric system is considered through so-called influence coefficient, which is the constituent of relative increment of the effective output losses against the feeding node of the regional network, resulting from the reactive load of the rest section of the system. All the calculation formulae for different initial conditions are given in the forms convenient for practical use.

Introduction of the work results. On the basis of the mathematical model gained in the dissertation, in the regional network of AES Telasi, the power distribution company of Georgia, and namely, in the 35-110-kV-voltage distribution network of substation D. NAVTLUGI the task of optimal compensation of reactive load was solved.

For setting up the equations set corresponding to the given task, out of the system parameters we applied only the relative increment of the effective output against 220-kV voltage of substation D. NAVTLUGI and the internal resistance of this node. The rest of the initial information was taken according to the data of the given distribution network. This resulted in a sharp reduction of the dimension of the equations set and the amount of the initial information.

Work approbation. The results of the scientific study were reported at the 71-st Open Scientific-Technical Conference of Students, Undergraduates and Post-graduates of Georgian Technical University (April, 2003) and at the Republican Scientific-Technical Conference (April, 2003). The report made at these conferences was awarded with a special diploma.

A number of issues of the work were listened to by the chairs of Electric Power Stations, Power Networks and Systems of Georgian Technical University (2001-2003) and by the Technical Council of Distribution Companies of AES Telasi (February, 2003) and UEDC (March, 2004).

Work publication. The principal results of the dissertation are published in five scientific articles.

Structure and volume of the work. The work consists of Introduction, six chapters, Conclusion and References with 63 works. The main body of the dissertation covers 151 printed pages, 38 drawings and 24 tables.

Brief description of the Work

Introduction of the dissertation accents the urgency of independent solutions to the technical tasks in individual regional distribution network of the electric system under the modern conditions of developmental trends of the market economy, and namely, the economic

efficiency of reducing the reactive power to be transferred through the network to the economically proved value.

Chapter 1 analyzes energy processes taking place in AC network and the peculiarities of reactive power in the electric system, as a concomitant event of the transferring process the reactive power. Reactive power in fact, is a convenient form in respect of analyzing the transition processes in AC network.

As it is known, even in case of balance of efficient output in the energy system there is a certain lack of reactive power, whose balancing needs a compensating equipment to be installed in the network. The change in the flows of reactive power is possible by use of this compensating equipment. At the same time, such equipment is advisable to be adjustable in accordance with the working mode of consumers.

The energy system, experiencing the lack of effective output, lacks the reactive power, as well. If compensating the lack of effective output at the expense of import from neighboring energy systems is an acceptable way, the same measure with the reactive power is apparently inefficient needing the installation of the equipment compensating the reactive load in the given system. The compensating equipment should be selected and located by ensuring its efficient functioning.

Compensation of reactive power is the purposeful generation or consumption of the reactive power by the compensating equipment.

Compensation of the reactive power is an efficient means in respect of regulating the voltage and effective output losses in the network. In this respect, adjustable compensating equipment, synchronous compensators, capacitors batteries and shunting reactors are more convenient.

The compensators, in respect of compensating the reactive power during the voltage changes in the network, are characterized by positive compensating effect whereas non-adjustable capacitors batteries have negative regulatory effect; however assembly and exploitation of the latter is easier and needs less amount of effective output from the network.

Despite certain negative features, the capacitors batteries in the distribution network are more frequently used than synchronous compensators, as they may be installed:

- At 0,38-kV-voltage value directly at a consumer (individual compensation);
- In distribution networks (group compensation);
- On the low-voltage (0,38, 6, 10 kV) bands of substations (centralized compensation).

Chapter 2 analyzes individual constituents of relative increment of the effective output losses against the node of the electric system considered, which are caused by the loads of the given node and other nodes of the network, respectively:

$$\sigma_i = \sigma_i^{`1} + \sigma_i^{ii},$$

Where

$$\sigma_i^1 = \frac{2}{U_n^2} R_{ii} Q_i \qquad \text{and} \qquad \sigma_i^{ii} = \frac{2}{U_n^2} \sum_{\substack{J=1 \\ j \neq 1}}^{n} R_{ij} Q_j$$

A formula to calculate the losses of the effective output according to nodal loads in the electric system may be expressed as follows:

$$\Delta P = \frac{1}{U_n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} R_{ij} \left(P_i P_j + Q_i Q_j \right)$$

In the given formula, the node generation is used with the 'plus' sign, and the load is used with the 'minus' sign.

Given this is the case, the functional relationship $\Delta P(Q_i)$ is expressed as it is shown in Fig. 1, showing the character of reduction of the effective output losses in the network during the reactive load compensation in the $_i$ node.

At this time, σ_i^{ii}, a constituent of the relative increment of losses remains unchanged, and the absolute value of the constituent σ_i^1 decreases in proportion to the compensation and equals to zero in case of full compensation of the reactive load in the network. Reduction of constituent σ_i^1 is proportional to the internal resistance of the node.

Бэb. 1

Fig. 1

7
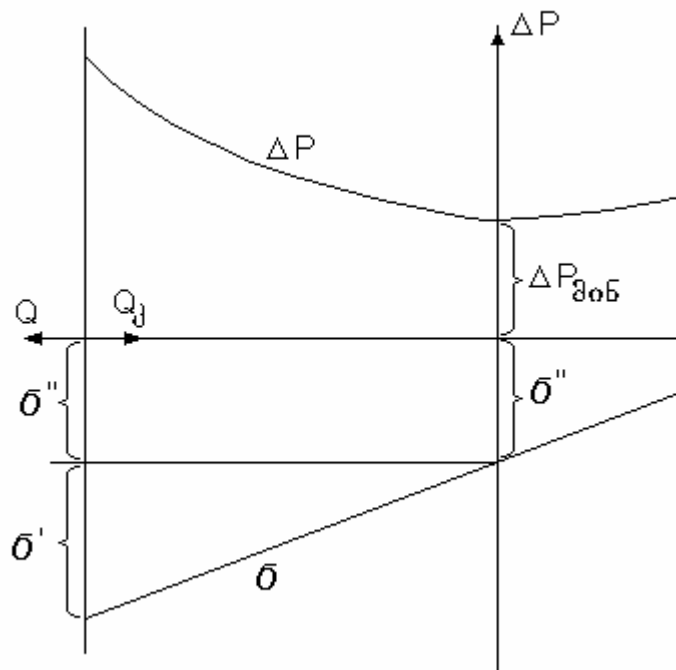
A simplified mathematical model of the task of optimal compensation is gained namely on the basis of the given regularity referred to in Chapter 5 of the dissertation.

As it may be seen from the diagram (Fig. 1), the advisability of compensation of the reactive load should be sought for the nodes with the greatest absolute value of relative increment of the effective output losses and with high internal resistance of the given node.

If not considering the costs of purchase, assembly and exploitation of the compensating equipment, the full compensation of reactive load in every node of the network in respect of reducing the losses of effective output is efficient. As all technical equipment including the compensating equipment need certain capital and exploitation expenses, there will exist a unambiguously defined limit value of the relative increment of losses in case of the given concrete network (Fig. 2), after which the further compensation of the load is impractical. This value is called an optimal value of the relative increment.

$$\sigma_{opt} = a \, ,$$

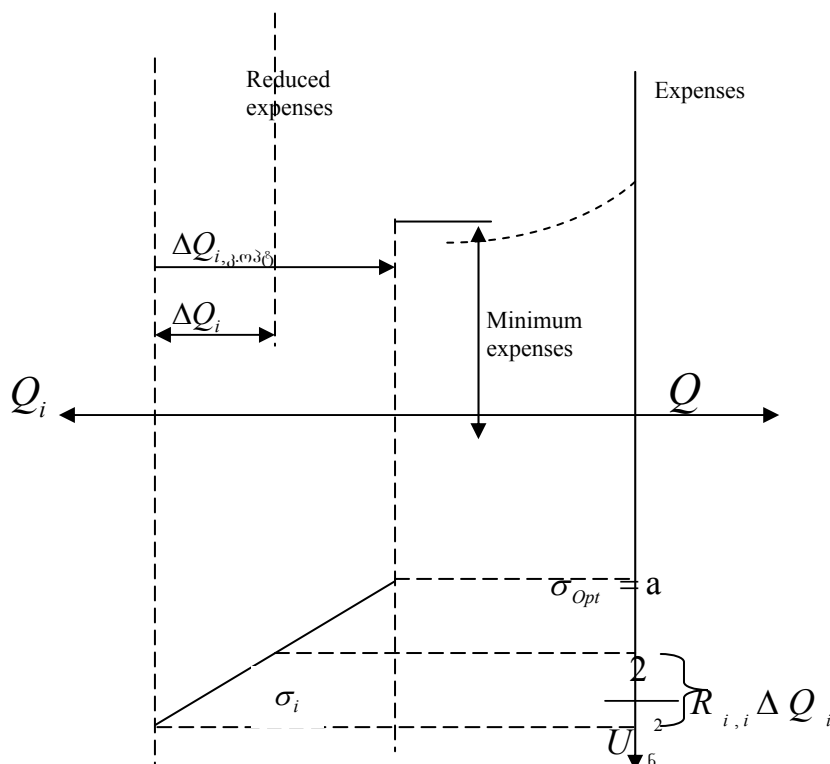Whose calculation formula is identified in Chapter 4.

Fig. 2

Chapter 3 analyzes the modern state of solving the task of optimal compensation of reactive load. Here the problem essence in respect of systematic approach is considered. A number of studies were dedicated to this problem in the former Soviet Union as well as beyond its borders. This is caused by the fact that in conditions of a rational solution to the problem a great technical-economic effect is readily reached.

Rational compensation of reactive load is an integral part of a scientific-technical complex of power industry, for following the balance of the reactive power in the electric system, about its one-third is to be generated by compensating equipment installed close to consumer.

Many-year-long studies in the given field were directed towards the issue of reducing the dimension of the set task and overcoming the informative isolation of individual sub-systems, resulting from departmental subordination of these sub-systems and the different capabilities to gather the initial rated information varying together with the different working modes of the network.

All available results of the study in the above-mentioned direction, as it is outlined in the work "Choice of compensating equipment at designing electric network" (1990) by Kovalev I. (Ковалев И.Н. Выбор компенсирующих устройств при проектировании электрических сетей, - М.: Энергоатомиздат, 1990), can be divided into two groups. The first group incorporates the methods of equivalenting of individual systems, and the second group incorporates a so-called method of partial calculation, which is a different approach.

Zhelezno I. in his work "Compensation of reactive power and boosting electric power quality" (Moscow, Energoatomizdat, 1985) (Ю.С. Железко. Компенсация реактивной мощности и повышение качества электроэнергии, М.: Энергоатомиздат, 1985) recommends $P(t)+jQ(t)$ diagram to be given in the nodes of connecting the extra-high-voltage transmission lines creating the energy power system to the main network, which diagram will be determined by an independent calculation. This method enables to determine the total value of input reactive power $Q_Э$ after optimization of the reactive load of each distribution network included in 110-500-kV-voltage energy power system, after which an independent task about optimal distribution of $Q_{,Э}$ power between the nodes of the given distribution network is set.

A number of authors in their works recommend the distribution network to be changed for an equivalent active resistance calculated by the known power losses. In the opinion of other researchers, much easier equivalenting in 6-35-kV-voltage network is possible and namely, the equivalent resistance of the mentioned voltage network may be gained by consecutive and parallel summing up of the resistances in the branches of the diagram tree. The authors call their method a partial one effective for relatively short 6-10-kV-voltage radial and mains lines what is more characteristic to industrial lines. [Fundamentals for installing industrial network

by Kayalov G., Kadjan E. Kovalev I. Kurenyi E. Moscow, Energy, 1978]. [Основы построения промышленных сетей/ Г.М. Каялов, Э.А. Каджан, И.Н. Ковалев, Э.Гю Курений. М.: Энергия, 1978]. This method implies localization of the task of compensation of reactive load.

In most cases of formulation of the task of compensation of reactive load referred to in the scientific-technical literary sources, the criterion function is formulated as reduced expenses and the issue of minimizing this function is considered. In other cases of task formulation the total power of compensating equipment is considered known and in such a case the task considers the issue of optimal distribution of this power between the network nodes.

A number of authors (Arzamastsev D., Sklyarov I.) (Арзамасцев Д.А., Скляров Ю.С.) offer to consider the task if admitted that on the basis of technical and engineering considerations, the places of the compensating equipment installation are given.

Some authors (Kayalov G., Molodtsov V.) (Каялов Г.М., Молодцов В.С.), based on the mathematical tasks of quadratic programming, offer a matrix technique so that the solution procedure for a complex equations set representing the regime of electric system with compensating equipment is to be changed for the calculation of the optimal values of the power of the equipment by applying ready matrix formulae.

A relatively successful special method is the expenditure potential method, referred to in the works by a number of authors (Mearovitch M., Mako D., Takakhara I., Kholmskyi V., Sherbina U.) (Меарович М., Мако Д., Такахара И., Холмский В.Г., Щербина Ю.В.). For the task solution those works consider a conditional diagram of the energy power system, which includes only pure resistances of the network elements and reactive loads of the nodes.

Authors Pospelov G., Sitch N. and Fedin V. (Поспелов Г.Е., Сыч Н.М. and Федин В.Т.) for the problem solution offer to use a so-called criteria method, which will enable to define not only the power and the points of installation of the compensating equipment, but the rational order of their installation, as well.

All the methods and approaches offered for solving the problem of optimal compensation of the reactive load have their pros and cons and are more or less successfully applied to the electric network of various designations and configurations.

Chapter 4 considers the hierarchy of the electric system and the peculiarity of the approach towards the solution to the problem of optimal compensation of the reactive load. In this chapter, by considering the unified substitution diagram drawn according to the vertical hierarchic structure of energy power system, the global problem of optimal compensation of the reactive load is set and the possibility to decompose this problem is explored what enables to consider the problem as individual, relatively simple, local tasks.

The electric system, according to the network voltages, is divided into four vertical hierarchical levels (Fig. 3).

During such a division it is understood that the electric network of level k has an electric coupling with only one node of the higher network $k+1$. There are main sources located at the fourth level of the hierarchy, any of which may be considered as a balance node.

At such an approach to the problem, in the autonomous distribution network of the 3-rd and lower levels the compensation of the reactive load has a certain influence on the power distribution within the feeding node and accordingly, in respect of the loss calculation, when solving a problem of a global nature, such an influence should be taken into account. Namely, in order to gain a more accurate solution to the task in the autonomous networks of levels III, II and I, β - the degree of compensation of the reactive load in the autonomous networks connected to other nodes of the feeding network should also be considered.

Distribution network 0.38 kV
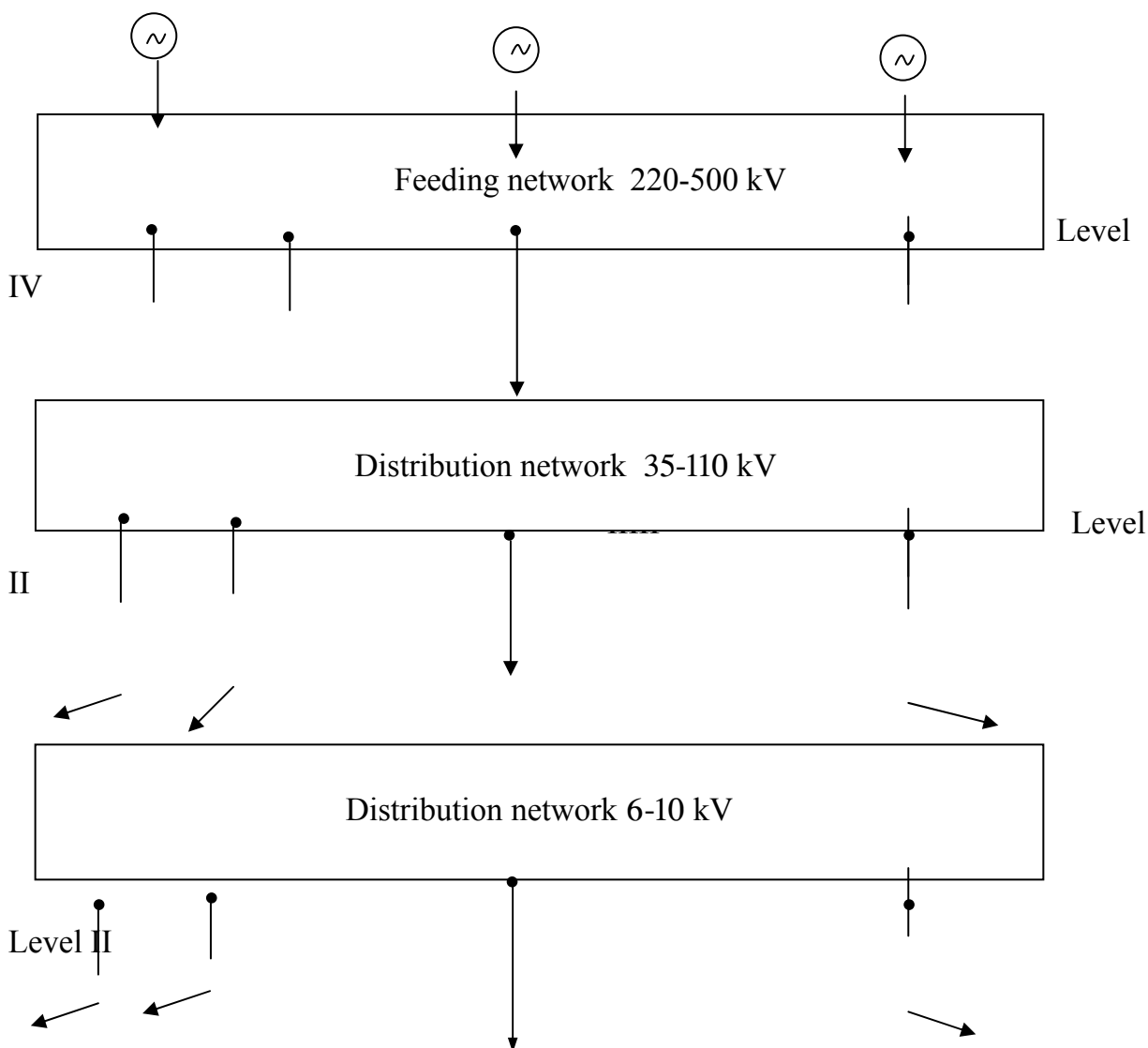
Level I

Fig. 3

Level I - 0.38-kV-voltage distribution network
Level II - 6-10-kV-voltage distribution network
Level III - 35-110-kV-voltage distribution network
Level IV - 220-500-kV-voltage feeding network

By considering the hierarchic structure, the problem of optimal compensation of the reactive load may be formulated differently according to our preference of the level of the network in whose nodes we wish to install the compensating equipment and whether the value of the reactive generation of the supply sources is known or is to be calculated. The number of these tasks amounts to eight, out of which task I is considered the most global one, as in case of this task, the values of optimal powers of the compensating equipment at all levels, along the vertical hierarchy and the optimal reactive loads of the generation sources will be determined.

Level of hierarchy	Nodes where compensating equipment is to be installed	Reactive generation of the feeding sources	Task index
I	$A_I, B_I, ...M_I$	To be fixed	I A
		Known	I B
II	$A_{II}, B_{II}, ...M_{II}$	To be fixed	II A
		Known	II B
III	$A_{III}, B_{III}, ...M_{III}$	To be fixed	III A
		Known	III B
IV	$A_{iV}, B_{IV}, ...M_{IV}$	To be fixed	IV A
		Known	IV B

In case of task of type A, the complex equations set is expressed as follows:

$$\frac{\partial \Delta P(Q)}{\partial Q_{f.\delta}} = \alpha \qquad\qquad f = 1, 2 \dots n_L$$

$$\frac{\partial \Delta P(Q)}{\partial Q_{f.\delta}} = 0 \qquad\qquad f = n_L+1, n_L+2 \dots n_L+n_G-1$$

$$\sum_{f=1}^{n_L}(Q_f + Q_{fk}) + \sum_{f=n_L+1}^{n_L+n_G} Q_{f_g} + \Delta Q = 0,$$

And for the task of type B, when the reactive loads of the electric stations are known, we will gain:

$$\frac{\partial \Delta \rho(Q)}{\partial Q_{f\delta}} = \alpha \qquad\qquad f = 1, 2 \dots n_L$$

$$\sum_{f=1}^{n_L}(Q_f + Q_{f_k}) + \sum_{f=n_L+1}^{n} Q_{f_G} + \Delta Q = 0$$

Where n_L and n_G - are the number of nodes of reactive load and generation, respectively; $n = n_L + n_g$ − is the total number of nodes in the network; a - is the optimal value of relative increment of effective output losses:

$$a = -\frac{1}{\tau}\left[\frac{(E_6 + \alpha)K_0}{C_0} + \Delta P_\delta \% \cdot T_0 \cdot 10^{-2}\right]$$

Where τ - is the time of maximum losses, hrs.

E_n- is the normative efficiency factor of redemption of the initial capital costs of the compensating equipment;

α − is the costs of depreciation (wear and tear), repairs and maintenance of the equipment in relative units;

K_0 − is the specific value of the equipment;

$\Delta \rho_\delta \%$ − is the percentage of the effective output losses of the given equipment;

T_0 − is the duration of switched-on position of the equipment, hrs.;

C_0 − is the tariff for the electrical energy at the given step of voltage, GEL/MWhrs;

A model diagram of dependence $a = f(K_0, C_0)$ is referred to in Figure 4.
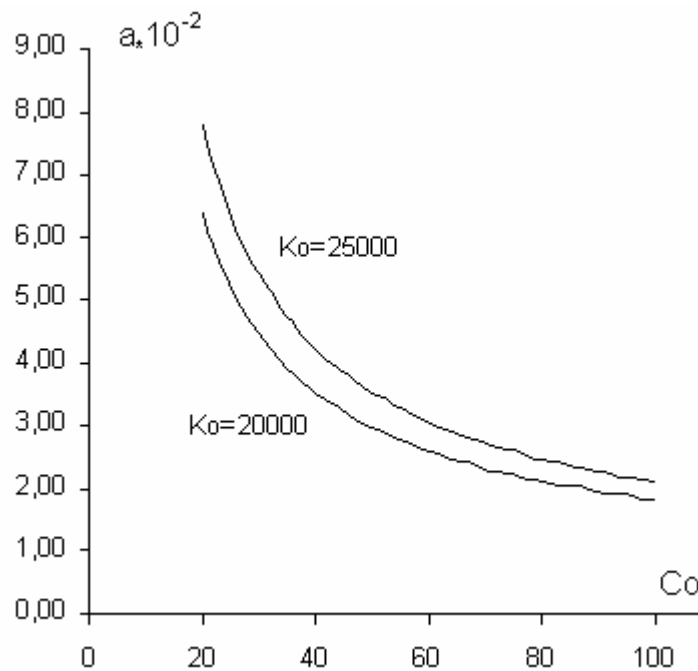
Fig 4

Chapter 5. As already mentioned, the problem of compensation of reactive load is an apparent system problem, including all network divisions of the power supply system.

The mentioned chapter shows a mathematical model, enabling to represent the set task in a relatively simplified form at the same time forming the criterion function with sufficient accuracy.

Bases for simplifying the global task of compensation of the reactive load are identified:

1. On the basis of hierarchical structure of the network it is demonstrated that the lower we move along one vertical of the hierarchy, the less essential the influence of loads and compensation of the nodes of the second vertical hierarchy on the value of optimal compensation of load in the nodes of the considered vertical is.

2. On the IV level of hierarchy, where the power transmission lines are in fact, always loaded with the load less than the natural power, the generation of the reactive power with the lines almost always exceeds the losses of reactive power in the same lines and as a result, at the given level of hierarchy, there is the excess reactive power what in a number of cases should be compensated with across-line reactors. Thus, there is a good cause to conditionally choose a node connecting to the IV level of the vertical structure under review as a balance node when fixing the task.

3. The I level of the vertical hierarchy is an independent 0.38-kV-voltage open network, whose transformer units with the voltage of 6-10/0.38 kV feed 0.38-kV-voltage single-

As the calculation analysis has demonstrated, the economic effect yielded in case of installation of single-phase compensating equipment at 0.38-kV-voltage consumer is so much insignificant that its value has no influence on the results of the task result. Thus, the bands of 6-10/0.38-kV-voltage transformer units of the distribution network are the most optimal installation points for the compensating equipment.

4. As it is known, the relative increment of the effective output losses against the balance node equals to zero, due to which fact in our case the IV level and all the rest vertical hierarchical levels connected to it will not be considered. In other words, a principle of system approach to the problem cannot be realized. In order to avoid such a situation, the node connecting the IV level of the considered vertical structure is viewed as a conditional balance node, against which the presence of the   of the IV level of the power supply system will be considered by means of R_{KK} - internal resistance and σ_K - relative increment of losses of the given node calculated against the balance node of the feeding network. Thus, following the above-mentioned, while setting the problem of optimal compensation of the reactive load in the distribution network, the III and I levels of the vertical hierarchy may be considered while the principle of system approach to the solution to the problem can be preserved with sufficient accuracy needed for engineering calculations. The mathematical model gained on the basis of the mentioned will be presented as follows:

$$\sum_{j=1}^{K} R_{ij} Q_{j_{\mathbf{k}}} = -\sum_{j=1}^{K} R_{ij} Q_j - \left[(1-\beta)\sigma_K^{"} - a\right]\frac{U_n^2}{2}. \qquad i,j = 1,2\ldots m$$

Where

$$\sigma_K^{"} = \sigma_K - \sigma_K^{'} = \sigma_K - \frac{2}{U_6^2} R_{KK} \cdot Q_{K\Sigma};$$

$$R_{ij} = R_{KK} + R_{ij}^{'};$$

$i, j -$ are the numbers of the node of the considered regional distribution network;

$K -$ is the total number of the nodes in the same network including the k node;

$R_{ij}^{'} -$ is the internal and mutual resistances of this regional network calculated against the

k node;

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σ_K − is the relative increment of the effective output losses against the balance node of the IV level;

$\sigma_K^{''}$ − is the constituent of the relative increment of the effective output losses caused by the configuration of the IV level and the rest of the regional network connected to it and the reactive nodal loads;

β − is the compensation degree of the reactive load in the rest of the regional network.

A simplified mathematical model for optimal compensation of the reactive load for low- and medium-voltage (6-35 kV) mains and radial networksis compiled in the same chapter.

This chapter provides a general description of the iterative process of solution to the equations set for optimal compensation of the reactive load in the ring main, according to which process the sequence of compensation according to the nodes is identified.

Chapter six is fully dedicated to the management issues of reducing the commercial losses in the distribution network.

The only way to reduce commercial losses in the network is combating plunder of electric power. The methodology offered in the dissertation enables to preliminary draw up a schedule for switching on and off the feeders at the sites with no counters to be used by the dispatcher of a distribution network aiming at minimizing commercial losses.

Conclusion

The results of optimal compensation of the reactive load in the distribution network of the electric system influence the mode of working of almost every element of the electric system. Such a solution to the task without application the principle of system approach results in certain errors, and simultaneous consideration of voltage networks of all stages of the system is in fact, impossible. Due to the mentioned, various methods of equivalenting are to be employed. The present work offers principally different methods of equivalenting.

The following conclusion may be made according to the results of the performed study:

1. For every regional network there is an optimal value of relative increment of the effective output losses, whose numerical value depends on the specific value and exploitation expenses of the compensating equipment, on the one hand, and on the electric power tariff in the given network and the duration of using the maximum active load in this network, on the other hand.

2. A calculation formula for optimal value of the relative increment of the effective output losses caused by reactive loads in the nodes is identified enabling to assess the compensation priority according to the nodes in advance.

3. A new and significantly simplified mathematical model of the task of optimal compensation of reactive load has been gained. At the same time, the principle of system approach to the task is maximally considered.

4. In respect of the action efficiency, it is economically advisable to perform the compensation of reactive load first in the electrically furthest node with a great absolute value of the relative increment of losses;

5. The principle of system approach in the mathematical model of optimal compensation of the reactive load of the considered regional distribution network is considered as the constituent of the relative increment of the effective output losses caused by the interaction between the given regional network and the rest part of the system;

6. The influence of the rest of the system in the mathematical model is given by so-called influence coefficient with its numerical value varying between 0,20-0,35;

7. A calculation formula allowing drawing a simplified equations set for the task of optimal compensation of the reactive load in the regional distribution network by considering the rest of the electric system has been identified;

8. Through the analysis of the hierarchical structure of the network, the work demonstrates that the lower we move along one vertical of the hierarchy, the less essential the influence of reactive loads of the nodes of the second vertical of the hierarchy and the compensation of such reactive loads is on the value of optimal compensation of the reactive load in the nodes of the considered vertical;

9. In respect of reducing the effective output losses, the recommended connection point for the compensating equipment is 6-10- or 0.38-kV-voltage bands of the 6-10/0.38-kV transformer units;

10. A mathematical model for optimal compensation of reactive load in the radial and main networks is given by an independent formula;

11. When applying the gained simplified mathematical model the dimension of the equations set decreases by several tens and more;

12. Aiming at reducing the commercial losses for the sections of the distribution network with no counters, a new methodology enabling a dispatcher to manage the network efficiently has been proposed.

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3. Makharadze G., Kikalishvili M. Optimal compensation of reactive load in the mains and radial electric networks. Energia, 4(16). 2000.

4. Kikalishvili M. Optimal compensation of the reactive load in the regional electric network. GTU, The 71-st Students', Undergraduates' and Post-graduates' Open Conference. Tbilisi. 2003.

5. Makharadze G., Kikalishvili M. Mathematical model of optimal compensation of reactive load in the regional distribution network. Works of Georgian Technical University. 2(452). Tbilisi. 2004