MINISTRY OF EDUCATION AND SCIENCE OF
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Rudny industrial institute

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OPTIMIZATION OF OPERATING MODES OF ELECTRICAL SUPPLY SYSTEMS BY STATIC CHARACTERISTICS OF POWER AND LOAD LOSSES

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The monograph presents a new solution to the current scientific problem - optimization of the operating modes of power supply systems by using the static characteristics of power and load losses that provides a comprehensive asPSSsment of power losses in the entire system at the same time, suitable for implementation in power supply systems of industrial enterpriPSS.

Mathematical modeling of power supply systems for industrial facilities is currently relevant and is one of the important issues in the electric power industry of the Republic of Kazakhstan.

The research is of interest for scientists, teachers, students, post-graduate students and undergraduates in energy specialties, as well as for leading specialists implementing energy-saving measures to save all types of energy resources in industrial enterpriPSS.

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INTRODUCTION

Operation efficiency of any industrial enterprise is determined to a large extent by the economy of the electricity supply system, which is especially important with significant specific electricity consumption and a high energy component in the structure of production costs. In this regard, it is necessary to solve the problem of optimizing the operating modes of power supply systems (PSS) in order to minimize losses for the transfer of energy from the energy system to consumers.

The static power characteristics of load nodes in the steady state, which are the dependences of the active P (U) and reactive Q (U) load powers from the voltage in the load node, are widely used in solving power supply problems, in particular: in calculating steady-state regimes; for choosing compensating devices and managing them; for regulating the voltage in the load nodes. Increasing the reliability and cost-effectiveness of PSS operation remains an urgent task at the present time.

Planning and operation of power supply scheme require the solution of various tasks characterized by increasing the reliability of power supply to consumers and a multitude of parameters that determine the state of interrelated and interacting process in synchronous and asynchronous engines, individual elements of the power supply system and the power system. The problems of analysis, calculation and optimization of operating modes are solved on the basis of application special methods and means of computer technology. The most widely used method is mathematical modeling.

Among the measures to optimize the operation of power supply systems, it is necessary to:

- conduct an analysis of power supply schemes for enterprises when changing the static characteristics of loads and power losses;
- optimize guid PSS, i.e. the cross-sections of the conductor cores of conductors in the guid networks are chosen not by the economic current density, but by the permissible current of the load or by the permissible voltage loss and in the maximum load modes, it is necessary to expect increased values of the total power losses in the elements of the electric network.

A great contribution to the solution of problems for optimizing the operating modes of PSS by using static load characteristics and power losses, ensuring the static stability of the motor load workload of power supply systems in enterprises was made by scientists: P.S. Zhdanov, V.A. Venikov, I.A. Syromyatnikov, I.M. Postnikov, B.G. Menshov, S.I. Gamazin, M.L. Levinshtein, S.V. Smolovik, Y.I. Ushakov, Y. A. Konyukhova, Yu.S. Zhelezko and others.

The problem of calculating energy losses has been worrying power engineers for a very long time. However, at the present time there are very few books on this subject thus very little things have changed in the fundamental arrangement of networks. But at the same time a fairly large number of articles are produced, where old data are refined and new solutions are offered for problems related to the calculation, normalization and reduction of power losses.

Despite a significant number of works in this field have not yet been properly developed methods of modeling and optimization of guild electricity supply systems, algorithms for calculating the characteristics of AMS and SD, the static characteristics of loads and power losses with reference to the calculation of normal operation modes of large PSS and their practical implementation. Most of the existing algorithms simplistically represent a circuit of networks that is complex in structure and configuration, equivalent to most of the load at 380V voltage, and do not fully take into account changes in the parameters of AMS and SD substitution circuit.

Static characteristics of active power losses characterize the efficiency of transmission, distribution and technological transformations of electrical energy to other types and necessary both for a numerical evaluation of this efficiency and for optimizing regimes in power supply systems.

Static characteristics of active power losses in the power supply system from this node of electric load characterize the total electrical power losses and can be represented in the form as follows:

$$\Delta P_{\Sigma}(U) = \Delta P_{\Sigma c}(U) + \Delta P_{\Sigma Д}(U), \tag{B.1}$$

Where: $\Delta P_{\Sigma c}(U)$ - total losses of active power in the elements of the electrical network;

$\Delta P_{\Sigma Д}(U)$ – total losses of active power in electric load engines;

U - voltage in the load node.

The power losses in the elements of the electrical network are divided into load losses ΔP_n, i.e. losses from the flow of the load current through the active resistance of the elements, and the loss in steel ΔP_{st} of magnetic transformer systems, practically independent of the load

$$\Delta P_{ln} = \Delta P_n + \Delta P_{st.} \tag{B.2}$$

Losses of active power in electric motors are divided into losses in stator windings ΔP_1, rotor ΔP_2 and loss in steel of magnetic systems $\Delta P_{ст}$

$$\Delta P_{la} = \Delta P_1 + \Delta P_2 + \Delta P_{st}. \tag{B.3}$$

The power losses in the load motors have practically no difference from the losses in the elements of the electrical network and therefore must be taken into account in the static power loss characteristics. It should also be remembered that load losses (including losses in engine windings) and losses in steel are significantly different depending on the voltage at the load node. The first ($\Delta P_н$) are determined by the relation

$$\Delta P_n \cong \frac{P^2(U) + Q^2(U)}{U^2} R, \tag{B.4}$$

Where: P(U) and Q(U) – active and reactive power transmitted through an element with resistance R, which increase with decreasing voltage. The second (ΔP_{st}) are defined by the relation

$$\Delta P_{st} \cong \frac{U^2}{R_m(U)}, \tag{B.5}$$

where R_m – the active resistance of the magnetization branch and the losses decrease with decreasing voltage. The ratio of these types of power losses, which are ultimately determined by the load factors of electric motors, essentially determines the type of static power loss characteristics.

The static characteristics of power losses in relation to the power supply system (up to 1 kV) deserve special attention for the following reasons:

1. The cross-sections of the conductor cores of conductors in the guid networks are chosen not by the economic current density, but by the permissible current of the load or by the permissible loss of voltage. Therefore, in the modes of maximum load, one should expect increased values of total power losses in the elements of the electrical network in transmitted power fractions. Small lengths of guild networks sections are excessively compensated by the number of connections. For example, in the guid transformer with $S_{ном}$ = 1000 kVA in average are connected over 100 power receivers.

2. A considerable proportion of the electric load in the guid of PSS is made up of asynchronous motors (AM) with a short-circuited rotor with a power of 1 to 4 kW, the efficiency of which is in the range of 0.75-0.85, i.e. power losses in such AM in fractions of the power consumption are commensurate with the total power losses at all previous stages of PSS transformation. Therefore, electric power losses in AM constitute an essential part of the total losses in the guid of PSS and to a large extent determine the type of static characteristics.

3. The average coefficients of AM loading of PSS guid by active power are Kl = 0,5 ÷ 0,7. At the same time, the power losses in the steel of magnetic systems are comparable to the load losses (or exceed them). Considering the essential dependence of power losses in steel on the voltage at the motors terminals, it becomes necessary to optimize the stress regimes on the bus bars of the guid transformer substations (TS).

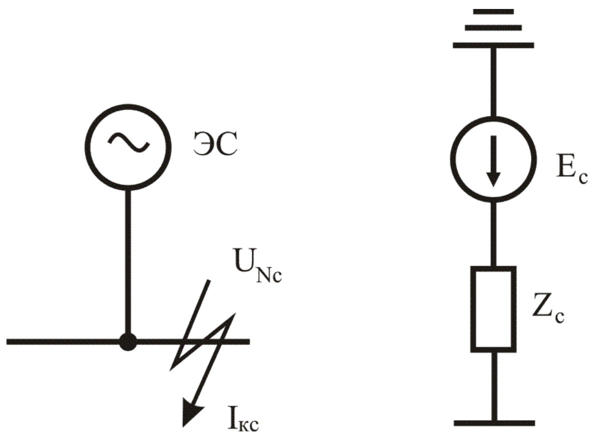
The determination of the static characteristics of power losses based on a physical experiment, and moreover their separation into components in accordance with the expressions (B.1) - (B.3), is practically not realizable. The only real way to determine them is calculation and experimental computer studies of mathematical models of guid PSS. The solution of the task is complicated by the branching of the guid network, the length of which is measured by meters, and the presence in the guids of several dozen to several hundred different types of electric motors (including foreign production) with a rated power from 0.3 kW to 400 kW, than in 1000 times.

1. MODELING OF ELECTRICAL SUPPLY SYSTEM AND INSTALLED OPERATING MODES

The industrial power supply system (IPSS) consists the following main parts: the external power supply network, which serves for connection to the electrical system and transmission of electricity to the industrial enterprise; network of internal power supply, intended for electricity distribution to consumers; electricity consumers, most of which are electric motors.

1.1 Modeling of the structure, configuration and condition of the industrial power supply system

The electrical system is an element that characterizes the generalized source properties of electrical energy relative to the place of IPSS connection. The total power of generators of electric stations is incommensurably greater than the capacity of IPSS load. This makes it possible to represent the electric system (Fig. 1.1a) with a source of ЭДС$\underline{E}_c$ (EMFE) with constant amplitude, phase and frequency applied beyond the equivalent complex resistance $\underline{Z}_c$ (Fig. 1.1, b).



а) б)

Figure 1.1 - The electrical system (a) and its substitution circuit (b)

The initial data for calculating the parameters of the substitution circuit can be the rated voltage of the electrical network at IPSS U_{NC} and K3 junction point and the fault current at this point from the electrical system $I_{кс}$.

Elements of the electric network - transmission lines (air, cable, current conductors), transformers (two-winding, triple-wound, split-wound), reactors (single, twin) - are represented by replacement circuits in the form of electric circuits with one (Figure 1.2, a) or three (Fig. 1.2b) concentrated complex resistances. These substitution schemes were obtained on the basis of the following assumption: the conductivity of the electric network elements and the free components of the electromagnetic transients in these elements are not taken into account. The parameters of the substitution scheme are determined through the catalog data of electrical networks elements.

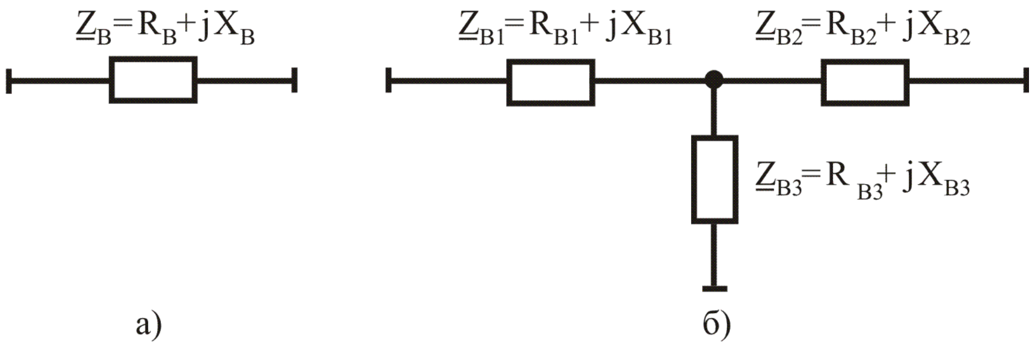


Figure 1.2 - Schemes of electric network elements substitution:
a - power line, two-winding transformer, reactor;
b - transformers with split winding and triple-wound, double reactors

Switching devices (SD), which can be classified as power switches, disconnectors and separators are special elements of the power supply system, for which two states are possible: on (with zero resistance) and off (with infinite resistance). With the help of SD reconnections are carried out in electric networks: switching off the damaged elements by relay protection, switching related to the operation of emergency control automatics (automatic reclosing, automatic resetting, etc.) and the automatic control system operation of the power supply system.

The scheme of substitution of IPSS for electric energy consumers is a set of replacement schemes for individual elements and switches connected in the same sequence as in the real system. Elements of the substitution scheme are: branches with complex resistances $\underline{Z}_b = R_b + jx_b \left(Z_b = \sqrt{R_b^2 + x_b^2} > 0 \right)$; switches; nodes (joints of two or more branches, branches with a switch or branches with a load). We introduce the notation: the total number of branches is n_b; number of SD – n_{sw}; the number of nodes is – n_j

All nodes, switches and branches must be numbered with arbitrary integers. The node corresponding to SIS of the electric system E_c (Fig. 1.1, b) is assigned the number zero, the remaining numbers from 1 to n_y. In an arbitrary order, SD (numbers from 1 to $n_{вк}$) and branches (numbers from 1 to $n_в$) are numbered. Branches belonging to the same element (Figure 1.2, b) are numbered sequentially. In addition, the branches of the substitution circuit are given a direction that coincides with the direction of active power transmission in them under normal conditions. In accordance with the direction for each branch, you can define the start and end nodes. We define the following integer arrays of dimension nb for the branches of the scheme for replacing the power supply system: an array of initial nodes JN; an array of finite nodes JK; array of types of electrical network elements JE. The type of elements is specified by pre-selected integers, for example: JE = 1 - electrical system; JE = 2 (3; 4) - two-winding transformers (with split winding, triple-wound); JE = 5 (6) - Single reactors (dual); JE = 7 (8; 9) - power transmission lines cable (current conductors, air).

We also define the following integer arrays of dimension nvk for circuit breakers in the scheme for replacing the power supply system: arrays JB1 and JB2 of the nodes that limit the switches; array of states of JCBK switches. In a replacement scheme, any of the switches is bounded by two nodes, one of which (any) will go into the JB1 array and the other into the JB2 array. The SD status is identified by pre-selected integers, for example JCBK = 0 - off; JCBK = 1 – enabled. Thus, any configuration of the electrical network of IPSS can be described by arrays JN, JK, JB1, JB2; the types of electrical network elements are uniquely determined by the array JE; the state of the electrical network - by the JCBK array, i.e. the above integer arrays can be used to analytically specify the initial configuration data, the types of elements, and the state of the electrical network of the EIT. In addition, the JE array can simultaneously serve as an indicator of what source data should be entered for a given element of the electrical network and by what formulas to calculate the parameters of the replacement circuit. As a result, a column matrix $\underline{Z}_в$ of the complex resistances of the branches of the PSS replacement circuit can be compiled. The nodes of the general substitution scheme can be divided into the following groups of nodes: the industrial complex load; synchronous derivations of synchronous motors; asynchronous motors; other nodes.

The unit of industrial complex load is a section of the switchgear (SG), to which is connected an arbitrary number of SM, AM and other electric load, accounted for by the static characteristics of active and reactive power, depending on the voltage in the node:

$$\left.\begin{aligned} \tau_{pr} &= P_{prN}\underline{U}^{\gamma_P}; \\ Q_{pr} &= P_{prN}\underline{U}^{\gamma_Q}, \end{aligned}\right\} \tag{1.1}$$

where P_{prN} и Q_{prN} - active and reactive power at the rated voltage in the load node ($U_y = U_{yN}$); γ_P and γ_Q - indicators of the degree characterizing the dependence of the active and reactive power on the voltage. The most general scheme for replacing the industrial complex load node is shown in Fig. 1.3: to i node is connected to ni synchronous motors, mi asynchronous motors and other load $\underline{S}_{пр\ i}=P_{прi}+jQ_{прi}$, determined by the static characteristics. Resistances $\underline{Z}_{вСД}$, $\underline{Z}_{вАД}$ are equal to the sum of the electric network elements resistances located between the section of the reactor and the terminals of the synchronous or respectively asynchronous motors.

Denote the total number of nodes of industrial complex load in the replacement scheme as n_c, the number of SM in the power supply system as $n_{СД}$, the number of AM in the power supply system is $n_{АД}$. Accordingly, we number the nodes of the industrial complex load from 1 to n_c; the nodes corresponding to the derivations of SM from 1 to $n_{СД}$; the nodes corresponding to AM derivations from 1 to $n_{АД}$.

For nodes of IPSS replacement scheme, we specify the following integer arrays: an array of JCK dimension n_c of the numbers of industrial complex load nodes; JSD array of dimension $n_{СД}$ number of nodes corresponding to SM derivations; JAD array with the dimension $n_{СД}$ of node numbers corresponding to the derivations of AM. These arrays unambiguously determine the structure of the nodes in IPSS substitution scheme.

The arrays characterizing the structure of the nodes of the replacement circuit, together with the arrays characterizing the configuration, the types of elements and the state of the electrical network, make it possible to determine whether SD and AD belong to the nodes of the industrial complex load and to calculate the generalized parameters of the electric network. The latter include: $\underline{Z}_{bSD}$ arrays ($\underline{Z}_{bAD}$) of complex resistances between the derivation of SM(AM) and the nodes of the industrial load to which they are connected; matrix $\underline{Z}_{j}$ of own and mutual nodal resistances relative to nodes of industrial complex load.

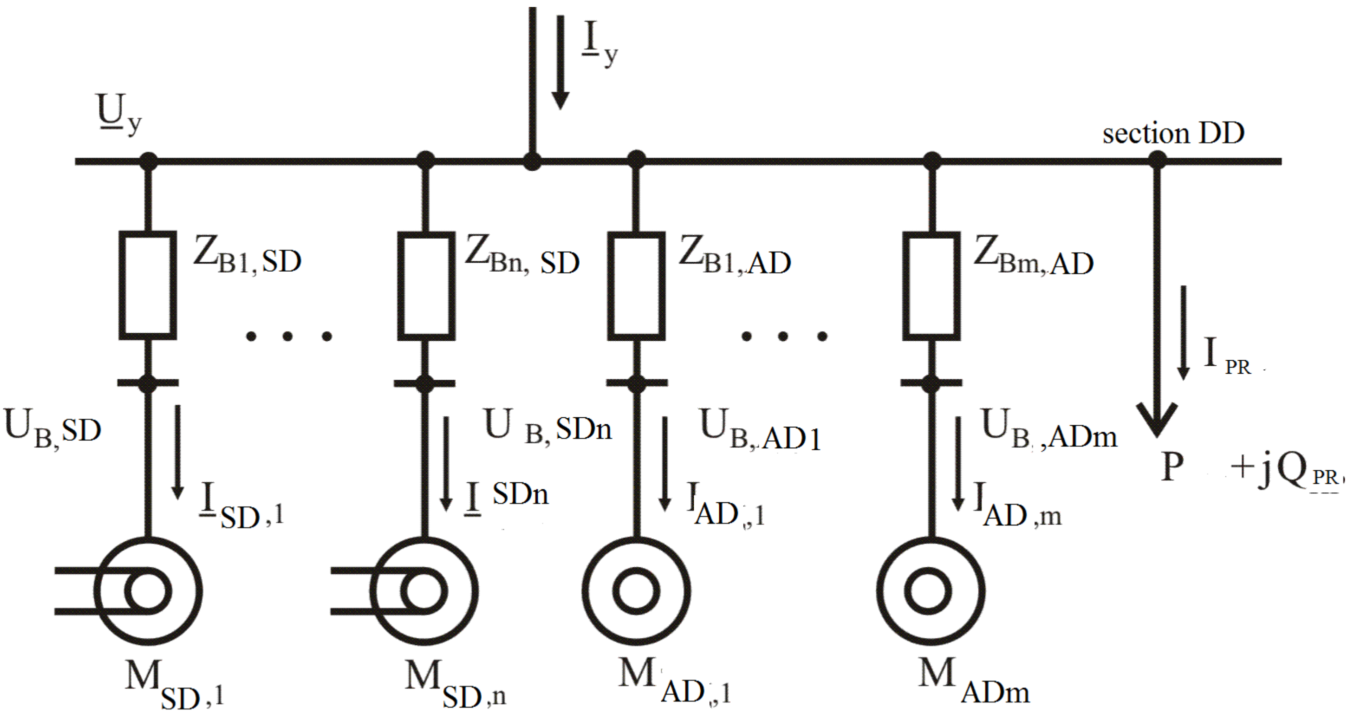


Figure 1.3 - Design scheme of the unit of industrial load

The electrical networks of IPSS are open, which greatly simplifies the calculation of the node resistances $\underline{Z}_{j}$. The advantage of the mapping the circuit method for replacing the electrical network of IPSS with passive generalized parameters is the compactness of the mapping of the matrices $\underline{Z}_{bSD}$, $\underline{Z}_{bAD}$ and $\underline{Z}_{j}$ in the form ($n_c^2 + n_{SD} + n_{AD}$) of complex numbers, ,than the total number of nodes in the substitution scheme.

The presence of separate closed circuits in IPSS, due, for example, to the parallel operation of the transformers, slightly complicates the algorithm for calculating the generalized parameters. The nodal resistance matrix in this case can be determined from the impedance matrix for an open network by the branch building method.

1.2 Features of modeling guid power supply systems

The guiding networks, in contrast to the supply networks of external power supply and distribution networks of the internal power supply, have the following features, reflected in the mathematical model of power supply systems with voltage up to 1 kV:

1. The range of elements of the guid network is much wider than in high-voltage electrical networks (current transformers, fuses, circuit breakers (automatic devices),

contactors, starters, switches, package switches must be added to the above-mentioned elements.The type of the element in the mathematical model is set by analogy with high-voltage networks of type (JE) with numbers from 10 to 16 (JE = 10 - current transformer, JE = 11 - automatic, etc.).

2. In spite of the fact that a greater number of low-voltage elements of the electric network are switching devices, they have a finite value of the electrical resistance, which is determined on the basis of the nominal parameters of the device (rated current and voltage). Resistance of current transformers is determined on the basis of data on the rated current of the primary winding and the accuracy class.

3. In low-voltage electrical networks, it is necessary to take into account the magnitude of the contact resistances between the elements, which is added to the resistance of the underlying network element.

1.3 Modeling of steady-state regimes of industrial power supply system

The quality of IPSS modeling is largely determined by the way modeling modes. The way of modeling the modes should allow to display the whole variety of possible states of SIS at the optimal expenditure of computer time and computer resources for calculations.

To simplify the calculation of the regimes in IPSS, it is expedient to distinguish three hierarchical levels [66]: the first one - from IPSS of the electrical system to the nodes of the industrial complex load; the second - from nodes of industrial complex load to engine outputs; the third is load engines. The structural scheme of the first hierarchical level of IPSS is shown in Figure 1.4.

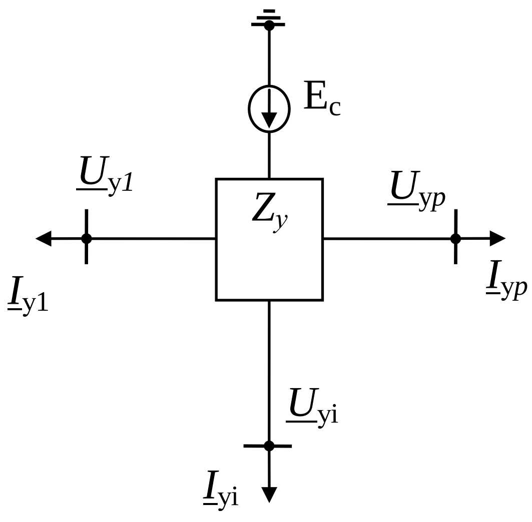


Figure 1.4 - The structural scheme of the first level of IPSS

The parameters of IPSS regime at this level are determined by the equation

$$\underline{U}_j = \underline{E}_c - \underline{Z}_j \underline{I}_j, \tag{1.2}$$

Where: $\underline{U}_j$ ($\underline{I}_j$) - matrix nodal voltages (currents), corresponding to the sections of HC in IPSS, i.e. nodes of industrial load;

$\underline{Z}_j$ - is the matrix of nodal resistances.

The input parameters of the first level are the node currents $\underline{I}_j$, which reflect the influence of the second and third levels; output parameters - nodal voltages $\underline{U}_j$ that characterize the influence of the first level on the rest.

For the second hierarchical level of IPSS (Figure 1.3), the following equations can be written:

$$\underline{U}_j = \underline{U}_j - \underline{Z}_{bm}\underline{I}_m; \tag{1.3}$$

$$\underline{I}_j = \underline{I}_{pr} + M_m \underline{I}_m, \tag{1.4}$$

Where: $\underline{U}_{ВД}$ - matrix of voltages on the motors terminals;

$\underline{Z}_{bm}$ - matrix of the electric network elements resistances in the circuit from the load node to the motor terminals;

M_m - the matrix of connecting the motors to load nodes;

$\underline{I}_m$- is the matrix of motor currents.

The input parameters of the second level with respect to the first are the node voltages $\underline{U}_j$; in relation to the third, the currents of the motors $\underline{I}_m$. Output parameters of the second level in relation to the first will be the node currents Ij, with respect to the third - the voltage at the terminals of $\underline{U}_{bm}$ engines. At the third hierarchical level of IPSS, the parameters of the regime are determined by the system of steady-state regimes equations of SM and AM. In this case, the input parameters for CAM will be the voltages at the motor terminals $\underline{U}_{bSD}$ and the excitation winding U_f and the moment of M_{MEX} mechanism resistance and for AM the voltage at the motor derivation $\underline{U}_{bAD}$ and the moment of the M_{mech} mechanism resistance. The output parameters of CAM and AM through which the effect of the engines on the mode of other levels SPE, are the currents of the motors $\underline{I}_{SD}$ and $\underline{I}_{AD}$.

To optimize the calculation of the mode of SM system can be represented by a substitution circuit (Figure 1.5) containing a branch with complex resistance

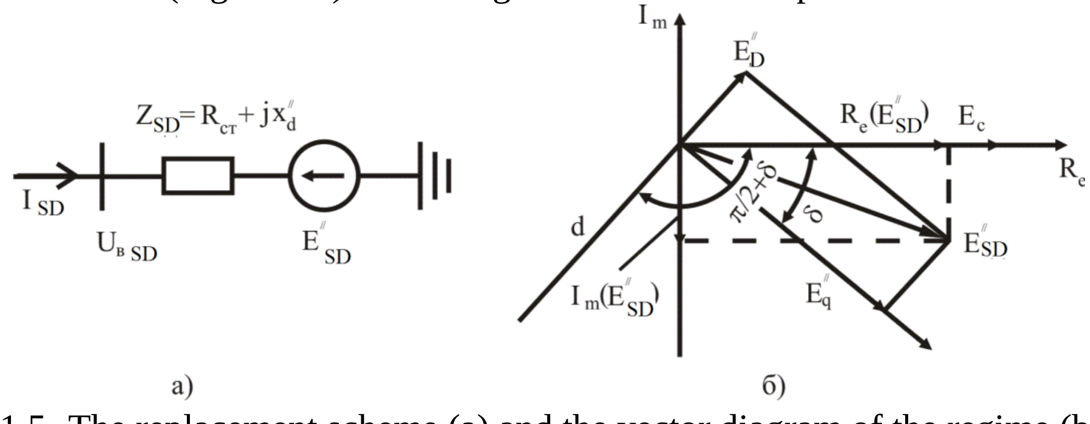


Figure 1.5- The replacement scheme (a) and the vector diagram of the regime (b) SM in IPSS

$$\underline{Z}_{SM} = R_{st} + jx_d'' \qquad (1.5)$$

and IPSS

$$\underline{E}_{SM}'' = \left(E_m'' + jE_q''\right)e^{-j\left(\frac{\pi}{2}+\delta\right)}, \qquad (1.6)$$

Where: R_{CT} - active resistance of the stator winding;

x_d'' - over-resistance on the longitudinal axis;

E_q'' - supertransient SIS along the transverse axis;

$E_Д''$ equivalent supertransient of SIS along the longitudinal axis, associated with IPSS of E_d'' by the following relationships:

$$\left.\begin{aligned} E_m'' &= E_d'' - I_q\left(x_d'' - x_q''\right); \\ E_m'' &= E_d''\frac{x_d''}{x_q''} + U_d\left(1 - \frac{x_d''}{x_q''}\right). \end{aligned}\right\} \qquad (1.7)$$

In the synchronous complex coordinate system Re, Im, which real axis coinciding with the direction of IPSS vector of the electrical system $\underline{E}_C$ (Figure 1.5, b), the components of IPSS $E_{СД}''$ are equal

$$\left.\begin{aligned} \mathrm{Re}\left(\underline{E}_{SM}''\right) &= E_М'' \sin\delta + E_q'' \cos\delta; \\ \mathrm{Im}\left(\underline{E}_{SM}''\right) &= E_М'' \cos\delta - E_q'' \sin\delta, \end{aligned}\right\} \qquad (1.8)$$

where δ - angle characterizing the position of the transverse axis q of SM rotor in a synchronous coordinate system.

The current of the stator winding of SM, according to the substitution schemes for the load node (Figure 1.3) and SM (Figure 1.5, a), can be calculated from the formula

$$\underline{I}_{SM} = \frac{\underline{U}_j - \underline{E}_{SM}''}{\underline{Z}_{bSM} + \underline{Z}_{SM}}. \qquad (1.9)$$

The replacement scheme for SM in relation to the remaining levels of IPSS (Figure 1.6) contains a branch with complex resistance

$$Z_{AM} = R_{st} + jx''_a \qquad (1.10)$$

and IPSS

$$\underline{E}''_{AM} = E''_a\left(\cos\delta_a - j\sin\delta_a\right) = E''_a e^{-j\delta_a}, \qquad (1.11)$$

Where: R_{STa} - active resistance of the stator winding;

x''_a - supertransitive inductive resistance;

E''_a - supertransitive IPSS;

δ_a - angle characterizing the position of the vector $\underline{E}''_{АД}$ relative to the real axis of the synchronous coordinate system.

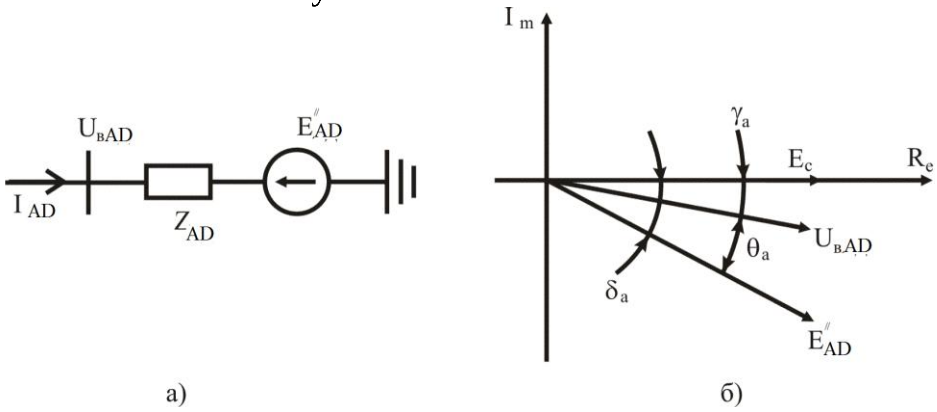


Figure 1.6 - The substitution scheme (a) and the vector diagram of the regime (b) AM

In accordance with the vector diagram (Figure 1.6, b)

$$\delta_a = \gamma_a + \theta_a, \qquad (1.12)$$

where γ_a – vector phase $\underline{U}_{вАД}$ relative to the real axis; θ_a – angle between vectors $\underline{E}''_{АД}$ and $\underline{U}_{вАД}$. In the etsablishe regime of AM

$$\theta_a = \operatorname{arctg}\left(T'_{2a} s_a\right). \qquad (1.13)$$

The current of the stator winding AM, according to the schemes of the load node substitution (Figure 1.3) and AM (Figure 1.6), can be calculated by the formula

$$\underline{I}_{SM} = \frac{\underline{U}_j - \underline{E}''_{AM}}{\underline{Z}_{bSM} + \underline{Z}_{AM}}. \qquad (1.14)$$

Taking into account the proposed schemes for replacing SM and AM, the industrial complex load node (Figure 1.7, a) can be represented by an equivalent substitution scheme containing a branch with equivalent nodal conductivity $\underline{Y}_{ec}$ and equivalent SIS $\underline{E}_{ec}$(fig. 1.7,b).

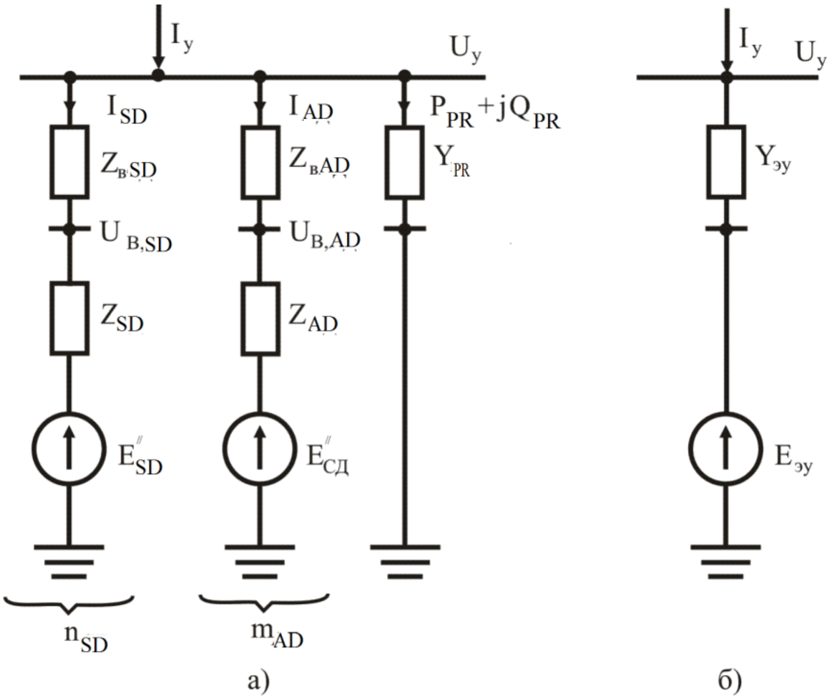


Figure 1.7 - The initial (a) and equivalent (b) schemes for

In general, to the load node can be connected n of SM, m of AM and other loads. Total conductance of the branch with SAM and AM relative to the load node replacing the industrial complex load node

$$\left.\begin{aligned} \underline{Y}_{SM} &= 1/\left(\underline{Z}_{bSM} + \underline{Z}_{SM}\right); \\ \underline{Y}_{AM} &= 1/\left(\underline{Z}_{bAM} + \underline{Z}_{AM}\right). \end{aligned}\right\} \tag{1.15}$$

Another load of the node can be represented by a branch with complex conductivity

$$\underline{Y}_{pr} = \frac{\hat{\underline{S}}_{pr}}{\left|\underline{U}\right|^{2}} = P_{prN}\underline{U}^{(\gamma_P-2)} - jQ_{prN}\underline{U}^{(\gamma_Q-2)}. \tag{1.16}$$

Thus, the parameters of the equivalent circuit for replacing the industrial complex load node (Fig. 1.7, b) are determined by expressions

$$\underline{Y}_{ec} = \Sigma\underline{Y}_{SM} + \Sigma\underline{Y}_{AM} + \underline{Y}_{ec}; \tag{1.17}$$

$$\underline{E}_{ec} = \frac{\Sigma\underline{E}''_{SM}\underline{Y}_{SM} + \Sigma\underline{E}''_{AM}\underline{Y}_{AM}}{\underline{Y}_{ec}}, \tag{1.18}$$

in which summation is performed over all SAM and AM connected to the node. The node current in accordance with the equivalent circuit of the load node replacement

$$\underline{I}_j = \left(\underline{U}_j - \underline{E}_{ec}\right) Y_{ec}\,. \tag{1.19}$$

1.4 Packages of applied programs for calculation and experimental studies of steady-state regimes of power supply systems

For computational and experimental studies of steady-state IPSS regimes, the software complex "SEZAM" was used as the base one, the software complex was written in the algorithmic Fortran language, a database of catalog data of the electric network and electric load elements, the maximum volume of characteristic elements of studied IPSS: 100 nodes of industrial complex load; 350 branches of the substitution scheme; 250 switches; 125 AM; 125 SAM.

With reference to the aims and objectives of the dissertation work, the complex was modernized, which consisted of:

- program processing for calculating the parameters of the replacement circuits for high-voltage and low-voltage induction motors (see Chapter 2);
- program processing for calculating the parameters of the replacement circuits for high-voltage and low-voltage synchronous motors of various types (see Chapter 3);
- algorithm development for calculating power losses in engines, taking into account the effect of current displacement in the damper windings of SAM and AM;
- program development for determining the static characteristics of power losses in both individual electric motors and in the entire power supply system;
- interface changes of the software complex to the tasks of studying the static characteristics of power losses.

1.5 Conclusion on the chapter 1

1. A method of modeling the power supply system based on the representation of IPSS by a three-level hierarchical structure and allowing to display IPSS of an arbitrary configuration of the structure and state in the form of compact matrices of the generalized parameters ZBAD, Z BCD and Zy are chosen.
2. For shop networks of electricity supply with voltage up to 1 kV, the range of elements of the workshop network is supplemented with elements such as current transformers, fuses, automatic switches (automata), contactors, starters, knife switches, batch switches.
3. The SEZAM complex was modernized in order to calculate the static characteristics of active power losses and loads.
4. Methods for optimizing the calculation of IPSS regime are considered, consisting in resolving the equations of nodal stresses with respect to the dominant parameters, using the Gauss-Seidel method for calculations and in calculating the optimal values of the initial approximation for nodal voltages.

2. PARAMETERS DETERMINATION AND CHARACTERISTICS OF ASYNCHRONOUS MOTORS WITH SHORT-TERM ROTOR

Asynchronous motors with squirrel-cage rotor (AMS) have found wide application due to a number of advantages in comparison with engines of other types. They are lighter, cheaper, easier to manufacture and operate, have rather high efficiency and power factor. The absence of contact rings and a brush mechanism makes these engines the most reliable and durable.

2.1 The substitution scheme and the basic relations characterizing the AMS regime

The AMS can be represented by a two-circuit substitution circuit (Figure 2.1), which is characterized by the following parameters: R_1 and $X_{\sigma 1}$ - active and inductive resistance of the stator winding scattering; R_{12} and X_{12} - active and inductive resistance of the magnetization branch, characterizing power losses in the steel of the magnetic system; $R_2(s)$ and $X_{\sigma 2}(s)$ are the active resistance and inductive resistance of the rotor winding scattering, which are reduced to the stator winding.

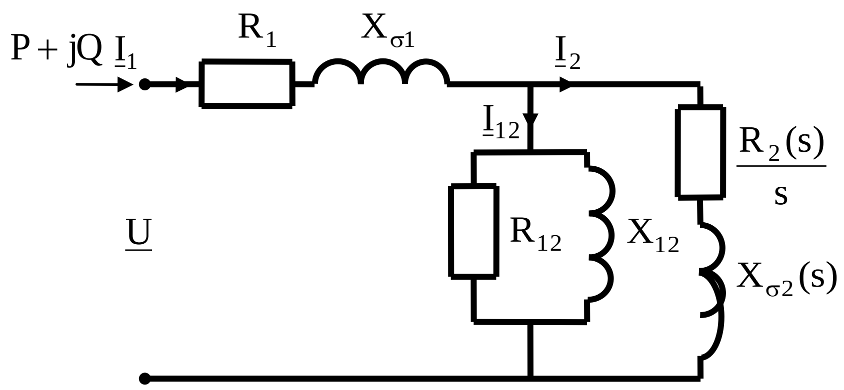


Figure 2.1 - The AMS substitution scheme

In AMS is necessary to take into account the phenomenon of surface effect, i.e. current displacement in the rotor winding. The degree of this displacement depends mainly on the frequency of the currents induced in the rotor winding, i.e. ultimately from slipping the engine. The effect of current displacement leads to a change in the active resistance and inductive resistance of the scattering of the rotor winding as a function of the sliding of the motor s, which is described quite accurately by the following dependences

$$\left.\begin{aligned} R_2(s) &= R_{2c} + \left(R_{2п} - R_{2c}\right)\sqrt{s}, \\ X_{\sigma 2}(s) &= \frac{X_{\sigma 2c} X_{\sigma 2п}}{x_{\sigma 2п} + \left(X_{\sigma 2c} - X_{\sigma 2п}\right)\sqrt{s}}, \end{aligned}\right\} \qquad (2.1)$$

Where: $R_{2c}(X_{\sigma 2c})$ – resistances corresponding to the synchronous regime (s = 0);

$R_{2п}(X_{\sigma 2п})$ – resistance, corresponding to the start-up mode (s = 1).

Along with the dependences (2.1) for describing the regularities of current displacement in AMS rotor, the following expressions are also proposed therefore it is necessary to find out which are more suitable for low-voltage AMS.

$$\left.\begin{aligned} R_2(s) &= \sqrt{R_{2c}^2 + \left(R_{2п}^2 - R_{2c}^2\right)s}, \\ X_{\sigma 2}(s) &= \frac{X_{\sigma 2c} X_{\sigma 2п}}{\sqrt{X_{\sigma 2п} + \left(X_{\sigma 2c}^2 - X_{2п}^2\right)s}}, \end{aligned}\right\} \tag{2.2}$$

The initial data for calculating the parameters of AMS substitution scheme are:

a) nominal data

P_N - nominal active power on AMS shaft;

U_N - rated voltage of the stator winding;

Cos φ_N - power factor in nominal modex;

η_N - coefficient of efficiency in the nominal mode of AMS;

s_N - AMS sliding in nominal mode;

b) startup mode data

$I_п$ is the frequency of the starting current in fractions of the rated current;

$M_п$ is the multiplicity of the starting torque in fractions of the nominal;

c) AMS critical regime data

M_{max} is the maximum electromagnetic moment in fractions of the nominal.

The parameters of the substitution scheme and AMS mode are defined in relative units. For the basic units, the nominal total power of AMS

$$S_б = S_N = \frac{P_N}{\cos\varphi_N \eta_N}; \tag{2.3}$$

and basic resistance

$$Z_В = \frac{U_N^2}{S_N}. \tag{2.4}$$

The exclusion from this system of relative units is advisable to do for the electromagnetic moment. It is customary to express it in fractions of the nominal useful moment M_N on AMS shaft.

The main parameters of AM mode can be represented through the parameters of the substitution circuit and sliding according to the following relations:

active power consumed from the network

$$P = U^2 \mathrm{Re}\left[\frac{1}{Z(s)}\right]; \tag{2.5}$$

reactive power consumed from the network

$$Q = U^2 I_m \left[\frac{1}{Z(s)} \right]; \tag{2.6}$$

stator current

$$I_1 = \frac{1}{|Z(s)|}; \tag{2.7}$$

electromagnetic moment

$$M = \frac{(1 - s_N)}{\eta_N \cos\varphi_N} \left[P - I_1^2 R_1 - U_{12}^2 / R_{12} \right] - \Delta M_{mee}, \tag{2.8}$$

where

$$Z(s) = R_1 + jX_{\sigma 1} + \left[\frac{1}{R_{12}} - j\frac{1}{X_{12}} + \frac{1}{\frac{R_2(s)}{s} + jX_{\sigma 2}(s)} \right]^{-1}, \tag{2.9}$$

equivalent complex resistance of the motor when sliding s

$$U_{12} = \sqrt{\left(U - \frac{PR_1 + QX_{\sigma 1}}{U} \right)^2 + \left(\frac{PX_{\sigma 1} - QR_1}{U} \right)^2}, \tag{2.10}$$

voltage on the magnetization branch of AMS replacement circuit,

$$\Delta M_{mech} = \frac{\Delta P_{mech.N}}{\eta_N \cos\varphi_N (1 - s_N)}, \tag{2.11}$$

the moment of resistance caused by mechanical losses of power in AMS itself ($\Delta P_{мех}$), which is added to the moment of resistance of the mechanism and together form the total moment of resistance on the shaft of AMS. In the future, the moment of resistance $\Delta M_{мех}$ in the operating modes of AMS is assumed to be constant, i.e. independent of slip, and therefore it can be determined from the nominal AMS regime.

The calculated parameters of the regime are expressed in terms of the parameters of the substitution circuit using the following relationships:
Starting electromagnetic moment and current (for s = 1)

$$M_{п1} = \frac{(1-s_N)}{\eta_N \cos\varphi_N}\left[\operatorname{Re}\left[\frac{1}{Z(s)}\right] - I_п^2 R_1 - U_{12}^2 / R_{12}\right] - \Delta M_{мех}, \qquad (2.12)$$

$$I_{п1} = \frac{1}{|\underline{Z}(s)|}; \qquad (2.13)$$

rated electromagnetic moment and reactive power (at $s=s_N$)

$$M_{N1} = \frac{(1-s_N)}{\eta_N \cos\varphi_N}\left[\operatorname{Re}\left[\frac{1}{\underline{Z}(s)}\right] - R_1 - U_{12N}^2 / R_{12} - \frac{\Delta P_{mee.N}}{1-s_N}\right], \qquad (2.14)$$

$$Q_{N1} = I_m\left[\frac{1}{Z(s)}\right]; \qquad (2.15)$$

the balance of the AMS reactive power in nominal mode (at s = 1)

$$Q_N = Q_{X\sigma1} + Q_{X12} + Q_{X\sigma2},$$

(where $Q_{X\sigma1}$, Q_{X12} и $Q_{X\sigma2}$ – components of the reactive power of AMS, due to the resistances $X_{\sigma1}$, X_{12}, $X_{\sigma2}$), which in the nominal mode can be converted to the form

$$\sin\varphi_N = X_{\sigma1} + \frac{U_{12N}^2}{X_{12}} + \frac{U_{12N}^2 X_{\sigma2N}}{\left(\frac{R_{2N}}{s_N}\right)^2 + (X_{\sigma2N})^2}, \qquad (2.16)$$

Where: R_{2N} and $X_{\sigma2N}$ – resistance of the rotor winding in the nominal mode, determined by the expressions (2.1), (2.2) for $s = s_N$ and

U_{12N} - voltage on the magnetization branch in AMS replacement circuit in the nominal mode, the square of which is equal

$$U_{12N}^2 = (1 - R_1\cos\varphi_N - X_{\sigma1}\sin\varphi_N)^2 + (X_{\sigma1}\cos\varphi_N - R_1\sin\varphi_N)^2;$$

maximum electromagnetic moment (at $s = s_{кр}$)

$$M_{max1} = \frac{(1-s_N)}{\eta_N \cos\varphi_N}\left[\operatorname{Re}\left(\frac{1}{\underline{Z}(s)}\right) - I_{кр}^2 R_1 - U_{12к2}^2/R_{12}\right] - \Delta M_{mee}; \qquad (2.17)$$

balance of active power losses in the nominal AMS mode (at $s = s_N$)

$$\Delta P_{\Sigma N} = R_1 + \frac{U_{12N}^2}{R_{12}} + I_{2N}^2 R_{2N} + \Delta P_{mee}\,, \tag{2.18}$$

Where: $\Delta P_{\Sigma N}$ – the losses of active power in the nominal AMS regime in fractions of SN, determined by expression

$$\Delta P_{\Sigma N} = (1 - \eta_N) \cos\varphi_N. \tag{2.19}$$

Relations (2.12) - (2.18) can be regarded as independent nonlinear equations for determining the parameters of AMS substitution circuit. With properly defined parameters of the replacement circuit, the calculated mode parameters must correspond to the catalog data, i.e. $M_{п1} = M_п$; $I_{п1} = I_п$; $M_{N1} = M_N = 1$; $Q_{N1} = Q_N = \sin\varphi_N$; $M_{max1} = M_{max}$.

To determine the parameters of AMS substitution circuit (R_1, $X_{\sigma1}$, R_{12}, X_{12}, $X_{\sigma2c}$, $X_{\sigma2п}$, R_{2c}, $R_{2п}$, $\Delta P_{мех}$) it is necessary to compile a system of nine independent equations and resolve this system with respect to the parameters of the replacement circuit. As seven equations, we can use the nonlinear equations (2.12) - (2.18), which correspond to AMS catalog data. Since the number of catalog data is less than the number of parameters of the substitution scheme, this system of equations must be supplemented by two more equations resulting from the stable relations between the AMS parameters. For each of the equations of the obtained system, it is necessary: to isolate the parameter of the replacement scheme that dominates in this equation; transform each equation to the optimal form, convenient for arranging calculations using the method of successive approximations with fast convergence; determine the initial approximation -for the dominant parameter of the substitution scheme in the equation.

1. Transformation of equation (2.12) for the starting torque. For the starting torque $M_п$, the following approximate expression is valid

$$M_l \cong \frac{(1 - s_N)}{\eta_N \cos\varphi_N} I_n^2 R_{2n}\,, \tag{2.20}$$

from which it follows that, as the dominant parameter in Eq. (2.12), we must take the resistance $R_{2п}$, and transform the equation itself to the following form, convenient for organizing the iterative solution process

$$Rl = R_{2l}^{(0)} \left(1 + \frac{\Delta M_n}{M_n}\right), \tag{2.21}$$

Where: $R_{2l}^{(0)}$ and R_{2l} – previous and subsequent approximation of the solution;

$\Delta M_l = M_l - M_{l1}$ – the difference between the catalog and calculated values (based on equation (2.12)) of the starting torque (with the convergence of the iterative process of solving equation $\Delta M_п \to 0$).

As the initial approximation of the resistance $R_{2п}$, we can take the value determined by the approximate relation (2.20).

$$R_{2l}^{(0)} = \frac{M_l \cos\varphi_N \eta_N}{I_l^2 (1 - s_N)} . \qquad (2.22)$$

2. Transformation of equation (2.13) for the starting current. For the starting current of the AMS, the following simplified expression is valid

$$\frac{1}{I_l} = Z_l \cong \sqrt{(R_1 + R_{2n})^2 + (X_n^{"})^2} , \qquad (2.23)$$

where $X_п^{"}$ – superconducting resistance of AMS in the starting mode, determined through the parameters of the substitution scheme by the ratio

$$X_l^{"} = X_{\sigma 1} + \frac{X_{\sigma 2n} X_{12}}{X_{\sigma 2n} + X_{12}} \cong X_{\sigma 1} + X_{\sigma 2n} . \qquad (2.24)$$

It follows from (2.23) that, as the dominant parameter in Eq. (2.13), it is expedient to take the resistance $X_l^{"}$, and transform the equation itself to the form

$$X_l^{"} = X_l^{"(0)} \left(1 - \frac{\Delta I_n}{I_n} \right), \qquad (2.25)$$

where $X_l^{"}$ and $X_l^{"(0)}$ – the subsequent and previous approximation of the solution; $\Delta I_l = I_l - I_{l1}$ – the difference between the catalog and calculated values of the starting current.

For the initial approximation of the resistance $X_l^{"(0)}$ we can take a value determined by the approximate relation (2.23)

$$X_l^{"(0)} = \frac{1}{I_n} \sqrt{1 - I_n^2 \left(R_1^{(0)} + R_{2n}^{(0)} \right)^2} . \qquad (2.26)$$

The initial approximation of the resistance $R_1^{(0)}$ will be determined below. Between the resistance $X_{\sigma 1}$ and $X_l^{"}$ there is the stable approximate relation

$$X_{\sigma 1} = 0{,}53 X_п^{"} , \qquad (2.27)$$

which can be used as one of the additional missing equations - to the system of equations (2.12) - (2.18) for determining the parameters of the replacement circuit.

3. Transformation of equation (2.14) for the nominal torque. For the nominal moment, the following simplified expression is valid

$$M_N = 1 \cong \frac{(1 - s_N)}{\eta_N \cos\varphi_N} \frac{s_N}{R_{2N} + 2R_1 s_N}, \tag{2.28}$$

where R_{2N} – the active resistance of the rotor winding at rated slip s_N. As the dominant parameter in equation (2.14), we must take the resistance R_{2N}, and convert the equation to the form

$$R_{2N} = R_{2N}^{(0)} \left(1 - \frac{\Delta M_N}{1 - 2R_1 \eta_N \cos\varphi_N} \right), \tag{2.29}$$

where R_{2N} and $R_{2N}^{(0)}$ - the subsequent and previous approximation of the solution; $\Delta M_N = 1 - M_{N1}$ is the difference between the catalog value and the calculated value of the nominal torque.

To determine the initial approximation of the resistance $R_{2N}^{(0)}$ let us use the following regularities of the nominal AMS regime.

The effective power on AMS shaft in the nominal mode will be

$$P_{в.N} = \eta_N \cos\varphi_N . \tag{2.30}$$

The active power in the rotor winding of AMS in nominal mode is

$$P_{2N} = P_{в.N} + \Delta P_{2N} + \Delta P_{mex.N}, \tag{2.31}$$

where P_{2N} – power losses in the rotor winding of AMS in nominal mode, equal to

$$\Delta P_{2N} = P_{2N} s_N. \tag{2.32}$$

From the expressions (2.30) - (2.32) it follows that

$$P_{2N} = \frac{\eta_N \cos\varphi_N + \Delta P_{mee.N}}{1 - s_N} \tag{2.33}$$

$$\Delta P_{2N} = \frac{\eta_N \cos\varphi_N + \Delta P_{mee.N}}{(1 - s_N)} s_N . \tag{2.34}$$

On the other hand, the losses ΔP_{2N} can be determined as follows

$$\Delta P_{2N} = I_{2N}^2 R_{2N} = \frac{U_{12N}^2}{\left(\frac{R_{2N}}{s_N} \right)^2 + (x_{\sigma 2N})^2} R_{2N} . \tag{2.35}$$

Neglecting in (2.35) the value $(x_{\sigma 2N})^2$ in view of the fulfillment of inequality

$$\left(\frac{R_{2N}}{s_N}\right)^2 >> \left(x_{\sigma 2N}\right)^2,$$

from expressions (2.34), (2.35) it follows that

$$R_{2N}^{(0)} = \frac{U_{12N}^2 s_N (1 - s_N)}{\cos\varphi_N \eta_N + \Delta P_{mee}}. \tag{2.36}$$

By the known values of the resistances R_{2N} and $R_{2п}$, the resistance value R_{2c} can be calculated from the first equation of the system (2.1) or (2.2).

$$\left.\begin{array}{l} R_{2c} = \dfrac{R_{2N} - R_{2п}\sqrt{s_N}}{1 - \sqrt{s_N}} \\ \text{and} \\ R_{2c} = \sqrt{\dfrac{R_{2N}^2 - R_{2п}^2 s_N}{1 - s_N}} \end{array}\right\}. \tag{2.37}$$

4. Transformation of the equation (2.15) for the rated reactive power. The expression (2.16) implies the relation

$$X_{12} = \frac{U_{12N}^2}{Q_N - X_{\sigma 1} - \dfrac{U_{12N}^2 X_{\sigma 2N}}{\left(\dfrac{R_{2N}}{s_N}\right)^2 + \left(X_{\sigma 2N}\right)^2}}, \tag{2.38}$$

from which it follows that, as the dominant parameter of equation (2.15), we can take the value X_{12} and transform the equation itself to the form

$$X_{12} = X_{12}^{(0)}\left(1 - \frac{X_{12}^{(0)}}{U_{12N}^2}\Delta Q_N\right), \tag{2.39}$$

where X_{12} and $X_{12}^{(0)}$ - subsequent and previous approximation of the solution; $\Delta Q_N = \sin\varphi_N - Q_{N1}$ – the difference between the catalog and calculated values of the reactive power of AMS in the nominal mode.

For the initial approximation of the resistance x_{12} we can take the value following from (2.30) with simplifications

$$X_{12}^{(0)} = \frac{U_{12N}^{2}}{\sin\varphi_N - X_{п}^{''}}, \tag{2.40}$$

where

$$U_{12N}^{2} = (1-\cos\varphi_N R_1 - \sin\varphi_N X_{\sigma1})^2 + \left(\cos\varphi_N X_{\sigma1} - \sin\varphi_N R_1\right)^2. \tag{2.41}$$

5. Transformation of the equation (2.16) of reactive power balance of AMS in the nominal mode. Equation (2.16), taking into account expressions (2.34) and (2.35), can be transformed to the form

$$\sin\varphi_N = X_{\sigma1} + \frac{U_{12N}^{2}}{X_{12}} + \frac{\eta_N\cos\varphi_N + \Delta P_{мех}}{(1-s_N)R_{2N}} s_N X_{\sigma2N} \tag{2.42}$$

and resolve it with respect to resistance $X_{\sigma2N}$

$$X_{\sigma2N} = \frac{\left(\sin\varphi_N - X_{\sigma1} - U_{12N}^{2}/X_{12}\right)(1-s_N)R_{2N}}{s_N\left(\eta_N\cos\varphi_N + \Delta P_{мех.N}\right)}. \tag{2.43}$$

In contrast to the equations (2.21), (2.25), (2.29), (2.39), the expression (2.43) is not iterative, but uniquely determines the value of $X_{\sigma2N}$ through other parameters of the substitution circuit and AMS catalog data. According to the known values of the resistances $X_{\sigma2N}$ and $X_{\sigma2п}$ from the second equations of systems (2.1) or (2.2), we can calculate the value $X_{\sigma2c}$

$$\left.\begin{aligned} X_{\sigma2c} &= \frac{X_{\sigma2N}X_{\sigma2п}\left(1-\sqrt{s_N}\right)}{X_{\sigma2п} - X_{\sigma2N}\sqrt{s_N}} \\ &\text{или} \\ X_{\sigma2c} &= \frac{X_{\sigma2N}X_{\sigma2п}\left(\sqrt{1-s_N}\right)}{\sqrt{X_{\sigma2п}^{2} - X_{\sigma2N}^{2}s_N}} \end{aligned}\right\}. \tag{2.44}$$

6. Transformation of equation (2.17) for the maximum electromagnetic moment. For the maximum moment, the following approximate relation is valid

$$M_{max} \cong \frac{(1-s_N)}{\eta_N\cos\varphi_N}\,\frac{\sqrt{R_1^2 + \left(X_{кр}^{''}\right)^2} - R_1}{2X_{кр}^{''}}, \tag{2.45}$$

where $X''_{кр}$ – the superconducting resistance of AMS at critical sliding ($s=s_{кр}$). From this relation it follows that as the dominant parameter of equation (2.17) one can take the resistance R_1, and convert the equation to the following form

$$R_1 = R_1^{(0)}\left(1 - \frac{\sqrt{\left(R_1^{(0)}\right)^2 + \left(X''_{кр}\right)^2}}{R_1^{(0)}}\frac{\Delta M_{max}}{M_{max}}\right), \qquad (2.46)$$

where R_1 and $R^{(0)}_1$ – subsequent and previous approximate resistance R_1;

$\Delta M_{max} = M_{max} - M_{max1}$ – the difference between the catalog and calculated values of the maximum electromagnetic moment of AMS. For the initial approximation of the resistance R1 in the calculations by the formula (2.46), we can take the value determined by the expression (2.45).

$$R_1^{(0)} = \frac{1 - 4\left(M_{max} X''_{кр}\dfrac{\eta_N \cos\varphi_N}{1 - s_N}\right)^2}{4M_{max}\dfrac{\eta_N \cos\varphi_N}{1 - s_N}}. \qquad (2.47)$$

When calculating the resistance X''_{cr} as a critical slip can be taken $s_{кр} = M_{max}s_N$.

It should be noted that, in accordance with expression (2.47), the value of resistance R_1 essentially depends on the value of the maximum electromagnetic moment M_{max} and the supertransition resistance X''_{cr}. When the M_{max} is changed to ±10 % the value R_1changes by ±20 %. When changing X''_{cr} by ±10 % the value R_1also changes by ±10 %. Standards for general-purpose asynchronous motors allow the difference between the real values of the parameters and those specified in the catalog data to: 15% for the starting torque; starting current - 20%; for the maximum electromagnetic moment - 10%. At such norms of permissible spread of catalog data, the spread in resistance values R_1 is ± 40 %. Therefore, along with the method of calculating the resistance R_1 based on the expressions (2.46), (2.47), it is expedient to use the method of calculating the resistance R_1. The essence of this method is based on the regularities of the change in the mass and size dimensions and the constituent losses of electrical energy in the series AMS. With constant current density in the stator winding and the maximum electromagnetic induction for AMS, the power losses in the stator winding, referred to the total rated power of the motor $S_{ном}$ (and hence the active resistance of the stator winding R1) vary in a power-law dependence on $S_{ном}$ with an exponent (-0.25) . Analysis of the aggregate series 4A engines of the basic design showed that the resistance R_1 with a good standard deviation (R^2 = 0,8279) can be determined by the formula

$$R_1 = 0{,}0802 \cdot S_{nom}^{(-0{,}2406)}. \qquad (2.48)$$

The difference between the formula (2.48) and the theoretical one (with exponent (-0.25)) is explained by the fact that neither the current density nor the maximum induction in AMS series remains constant.

Thus, it is necessary to analyze the calculation methods for the resistance R_1, based on the formulas (2.46), (2.47) and based on the formula (2.48) - and choose the one most suitable for the purposes of calculating the static power loss characteristics in the workshops SIS.

7. Transformation of equation (2.18) for the balance of active power losses in the nominal mode of AMS.

The sum of the power losses in the steel $\Delta P_{12,N}$ and the mechanical power losses $\Delta P_{мех.N}$ in the nominal mode, which can be conditionally called the idling power loss in the nominal mode $\Delta P_{x.N}$, as follows from the power loss balance equation (2.18), is equal to

$$\Delta P_{x.N} = \Delta P_{\Sigma N} - \Delta P_{1N} - \Delta P_{2N}, \tag{2.49}$$

where

$$\Delta P_{\Sigma N} = (1 - \eta_N) \cos\varphi_N - \tag{2.50}$$

total power losses in the nominal mode of AMS;

$$\Delta P_{1N} = R_1 - \tag{2.51}$$

loss of power in the stator winding in the nominal mode of AMS

$$\Delta P_{2N} = \frac{\eta_N \cos\varphi_N + \Delta P_{мech.N}}{(1 - s_N)} s_N - \tag{2.52}$$

loss of power in the rotor winding in the nominal mode of AMS.

The mechanical power losses and power losses in AMS steel make up a stable fraction of the losses $\Delta P_{x.N}$, on average is

$$\left.\begin{aligned} \Delta P_{мech.N} &= 0{,}3\Delta P_{x.N}, \\ \Delta P_{12.N} &= 0{,}7\Delta P_{x.N}. \end{aligned}\right\}. \tag{2.53}$$

Expression (2.52), along with (2.27), based on stable relationships between the parameters of AMS, can be used as the second missing equation to the system of equations (2.12) - (2.18) for determining the parameters of AMS substitution circuit.

From the expressions (2.49) - (2.53) it follows that

$$\Delta P_{мech.N} = \frac{0{,}3\left[\cos\varphi_N\left(1-\frac{\eta_N}{1-s_N}\right)-R_1\right]}{1+0{,}3s_N\ /(1-s_N)}, \tag{2.54}$$

$$\Delta P_{12N} = \frac{0{,}7\left[\cos\varphi_N\left(1-\frac{\eta_N}{1-s_N}\right)-R_1\right]}{1+0{,}3s_N\ /(1-s_N)}, \tag{2.55}$$

$$R_{12} = \frac{U_{12N}^2}{\Delta P_{12N}}. \tag{2.56}$$

Thus, we have compiled a system of nine independent equations that allows us to determine all nine parameters of AMS substitution scheme.

Calculations using the method of successive approximations are continued until the condition

$$|\Delta M_l| \cup |\Delta I_l| \cup |\Delta M_N| \cup |\Delta Q_N| < \varepsilon,$$

where ε =0,001 – given accuracy by the method of successive approximations.

For the final choice of the algorithm for calculating the parameters of AMS substitution circuit, it is necessary:

1. Choose from the expressions (2.1) or (2.2) the patterns of current displacement in the rotor that are most suitable for low-voltage AMS.

2. Investigate the calculation methods for the resistance R_1, one of which is based on the expressions (2.46), (2.47) and the other (2.48), and choose the static power loss characteristics of the in-plant PSS suitable for the purpoPSS of calculating.

2.2 Evaluation of algorithms for calculating the parameters of the low-voltage AMS substitution circuit

Among the algorithms for calculating the parameters of the AMS replacement circuit, presented in the previous section, it is necessary to choose the one that is most suitable for calculating the static characteristics of power losses in the workshop PSS. What is meant by the words "the most suitable"? Given the permissible spread of AMS catalog parameters from ± 10% to ± 20%, for different designs, different synchronous rotor speeds and different nominal powers of the AMS, the parameters of the replacement circuit should reflect the average trend of variation of individual power loss components, within the total losses determined by the efficiency of the AMS. Here, it is not important to determine accurately the parameters of the replacement circuit of each AMS (it is relative when using catalog parameters as the initial data, which is due to their allowable spread), and the average trend of their change on a large AMS set. There are several dozen to hundreds of AMSs in the workshop PSS, while maintaining average trends in the parameters of the substitution scheme for the error from determining the component losses in individual engines, in total power losses for such an amount, AMSs are mutually eliminated.

For calculating studies were compiled four programs for personal computers, implementing all four modifications of the algorithms:

- the program PAD1 (parameters of asynchronous motors) implements an algorithm in which the displacement of the current in the rotor is taken into account by the expressions (2.1), and the active resistance of the stator winding R_1 is calculated from the expressions (2.46), (2.47) through the maximum electromagnetic moment M_{max};
- the program PAD2 implements an algorithm in which the current displacement in the rotor is taken into account by the expression (2.2), and the calculation of the resistance R_1 is carried out by the expressions (2.46), (2.47);
- the program PAD3 implements an algorithm in which the current displacement in the rotor is taken into account by the expressions (2.1), and the calculation of the active resistance of the stator winding R_1 is carried out by the expression (2.48) in the form of a power function of the total rated power of the engine $S_{ном}$;
- the program PAD4 implements an algorithm in which the current displacement in the rotor is taken into account by the expression (2.2), and the calculation of the resistance R_1- according to the expression (2.48).

Thus, the programs PAD1 and PAD2 (respectively PAD3 and PAD4) differ only in the way of taking into account the current displacement in the rotor, and the programs PAD1 and PAD3 (respectively PAD2 and PAD4) - the method of calculating the active resistance of the stator winding. In other respects, the algorithms of all programs are the same. Let us consider the parameters of a number of AMSs differing in nominal power by more than 400 times.

AMS1: $P_{ном}$ = 132 kV; $\cos\varphi_N$ = 0,85; η_N = 0,935; s_N = 0,013; $I_п$ = 6,5; $M_п$ = 1,2; M_{max} = 3,1.The active resistances of the AMS replacement scheme calculated for all four programs are presented in Table 2.1a, and reactive ones in Table 2.1b.

Table 2.1a - Active resistances of the AMS replacement scheme

	R_1	$R_{2п}$	R_{2N}	R_{2c}	R_{12}	$\Delta P_{мех}$
PAD1	0,0279	0,0244	0,014	0,0126	74,74	0,005
PAD2	0,0205	0,0245	0,0141	0,0139	52,74	0,072
PAD3	0,0234	0,0245	0,0141	0,0127	59,46	0,0064
PAD4	0,0234	0,0245	0,0141	0,0139	59,46	0,0064
PAD1	0,0234	0,0245	0,0141	0,0127	59,53	0,0064
PAD2	0,0234	0,0245	0,0141	0,0139	59,19	0,0064

Table 2.1б - Reactive impedance of the AMS replacement circuit

	$x_{\sigma 1}$	$x_{\sigma 2п}$	$x_{\sigma 2N}$	$x_{\sigma 2c}$	x_{12}	$x''_{п}$
PAD1	0,077	0,0701	0,0893	0,0926	2,30	0,145
PAD2	0,0782	0,0712	0,0932	0,0936	2,35	0,1473
PAD3	0,0778	0,0708	0,0891	0,0922	2,315	0,1465
PAD4	0,0778	0,0708	0,0901	0,0904	2,32	0,1465
PAD1	0,0778	0,0708	0,091	0,0945	2,32	0,1464
PAD2	0,0778	0,0708	0,092	0,0925	2,32	0,1465

The last two lines in Table. 2.1a, b correspond to the initial data, when all the catalog parameters of the AMS were accepted as before, except for the maximum moment M_{max} which for the program PAD1 is equal to M_{max} = 3,145, and for the program PAD2 - M_{max} = 3,076.

From the analysis of the calculated parameters of the AMS replacement circuit, it follows that the programs PAD1 and PAD2 are very sensitive to the value of the maximum torque. If you change the program PAD1 M_{max} from the value of M_{max} = 3,1 to the value of M_{max} = 3,145, i.e. at 1.45%, the value of the active resistance of the stator winding changes from R_1 = 0.0279 to R_1 = 0.0234, i.e. on 16,2%. Similarly, for the PAD2 program: when the maximum torque is changed from M_{max} = 3.1 to M_{max} = 3.076, i.e. at 0.77%, the resistance value R_1 changes from R_1 = 0.0205 to R_1 = 0.0234, i.e. on 14,15%.

The permissible deviation of the maximum moment of the real AMS from the catalog data is ±10%. With such a spread of the maximum torque, the spread of resistances R_1 in programs PAD1 and PAD2 exceeds reasonable limits. Consequently, the use of the maximum moment (i.e., expressions (2.46), (2.47)) to calculate the active resistance of the stator winding at existing norms of the allowable spread of real values of M_{max} for an ADC of one type is not possible.

Comparing the methods of taking current displacement in the rotor, using formulas (2.1) and (2.2), it should be noted that using the formulas (2.2) (programs PAD2 and PAD4) the values of the active and reactive resistances of the rotor winding in synchronous (with index "c") and nominal (with index "N") modes are practically the same, while using formulas (2.2) (programs PAD1 and PAD3) these values differ more significantly. The general theory of current displacement in rotor windings shows that when the slip in the operating modes of the AMS changes (from s = 0 to s = $_N$), the current is not practically displaced in the rotor windings, and changes in the parameters of the rotor winding have a significant effect only for slip $s > s_{кр}$. This conclusion of the theory is better matched by the method of taking into account the displacement of the current in the rotor windings, based on the expressions (2.2). Therefore, the program PAD4 should be recognized as the most suitable for calculating the static power loss characteristics in the workshop PSS.

Let's check these conclusions on other AMSs.

AMS2: P_{nom} = 55 кВт; $\cos\varphi_N$ = 0,79; η_N = 0,92; s_N = 0,018; I_l = 5,5; M_l = 1,3; M_{max} = 2,7.

The active resistance of the AMS replacement circuit, calculated for all four programs, is shown in Table. 2.2a, and reactive - in Table. 2.2b. The last two lines of the table correspond to the maximum moment compared with the catalog data: for the program PAD1, M_{max} = 2.767, for the PAD2 program, M_{max} = 2.685.

Table 2.2a - Active resistance of the AMS replacement circuit

	R_1	$R_{2п}$	R_{2N}	R_{2c}	R_{12}	$\Delta P_{мех}$
PAD1	0,0392	0,0348	0,0201	0,0178	112,86	0,0032
PAD2	0,0253	0,0349	0,0204	0,02	50,13	0,0073
PAD3	0,0283	0,0349	0,0203	0,0181	56,84	0,0064
PAD4	0,0283	0,0349	0,0203	0,02	56,84	0,0064
PAD1	0,0283	0,0349	0,0203	0,0181	56,82	0,0064
PAD2	0,0283	0,0349	0,0203	0,02	56,83	0,0064

Table 2.2b - Inductive impedance of the AMS replacement circuit

	$x_{\sigma 1}$	$x_{\sigma 2п}$	$x_{\sigma 2N}$	$x_{\sigma 2c}$	x_{12}	$x''_{п}$
PAD1	0,0886	0,0816	0,1135	0,1208	1,87	0,1668
PAD2	0,0913	0,0842	0,1208	0,122	1,94	0,172
PAD3	0,0908	0,0837	0,1167	0,1242	1,92	0,171
PAD4	0,0908	0,0837	0,1185	0,1196	1,92	0,171
PAD1	0,0908	0,0837	0,1184	0,1265	1,92	0,171
PAD2	0,0908	0,0837	0,1193	0,1205	1,92	0,171

For AMSs of lower power, the same trends persist when calculating the parameters of the replacement circuit. Programs PAD1 and PAD2 are very sensitive to variations in the maximum torque. When the maximum torque varies from M_{max} = 2.7 to M_{max} = 2.767, i.e. at 2.48% in the PAD1 program, the value of the active resistance of the stator winding changes from R_1 = 0.0392 to R = 0.0283, i.e. by 27.8%. Similarly for the program PAD2: when changing from M_{max} = 2,7 to M_{max} = 2,685, i.e. at 0.55%, the value of the active resistance of the stator winding changes from R_1 = 0.0253 to R_1 = 0.0283, i.e. by 11.6%. Therefore, the use of the PAD1 and PAD2 programs under the conditions of the permissible norms of deviations of the real values of M_{max} from the catalog values seems to be unacceptable, since the value of the resistance R1 for such deviations of M_{max} can go beyond the permissible limits. The method of taking into account the current displacement in the rotor, based on the expressions (2.2) The general rules governing the displacement of current and for calculating the parameters of the AMS substitution circuit should be given preference to the PAD4 program.

The next engine is AMS3 with catalog data: P_{nom} = 15 кВт; $\cos\varphi_N$ = 0,85; η_N = 0,87; s_N = 0,026; $I_п$ = 5,5; $M_п$ = 1,5; M_{max} = 2,7. Table. 2.3a, b shows the design parameters of the substitution scheme. The last rows of the tables correspond to the maximum moment compared with the catalog data: for the program PAD1 M_{max} = 2,785, for the program PAD2 M_{max} = 2,712.

Table 2.3a - Active resistance of the AMS replacement circuit

	R_1	$R_{2п}$	R_{2N}	R_{2c}	R_{12}	$\Delta P_{мех}$
PAD1	0,0363	0,0399	0,0292	0,0271	23,84	0,0153
PAD2	0,0224	0,04	0,0297	0,0293	19,19	0,0194
PAD3	0,0385	0,0399	0,0291	0,0271	24,85	0,0146
PAD4	0,0385	0,0398	0,0291	0,0288	24,85	0,0146
PAD1	0,0386	0,0398	0,0291	0,0271	24,88	0,0146
PAD2	0,0385	0,0399	0,0291	0,0288	24,85	0,0146

Table 2.3b - Inductive impedance of the AMS replacement circuit

	$x_{\sigma 1}$	$x_{\sigma 2п}$	$x_{\sigma 2N}$	$x_{\sigma 2c}$	x_{12}	$x''_{п}$
PAD1	0,0881	0,0808	0,1128	0,1221	2,07	0,1659
PAD2	0,091	0,0835	0,1205	0,1223	2,16	0,1714
PAD3	0,0876	0,0803	0,1118	0,1209	2,06	0,1649
PAD4	0,0876	0,0803	0,1136	0,1151	2,07	0,1649
PAD1	0,0875	0,0803	0,1118	0,1209	2,06	0,1649
PAD2	0,0876	0,0803	0,1128	0,1143	2,07	0,1649

From the analysis of the data of Table. 2.3a, b can be drawn the following conclusions: the programs PAD1 and PAD2 are very sensitive to the variation of the maximum moment; the method of taking into account the displacement of current in the rotor, based on the expression (2.2), better reflects the picture of the general theory of current displacement; Preference should be given to the program PAD4.

The next AMS4 engine with catalog data: Pnom = 4 кВт; cos φ_n = 0,81; η_N = 0,82; s_N = 0,04; Iп = 5,0; Mп = 1,5; Mmax = 2,6. Table 2.4a, b shows the parameters of the substitution scheme. The last two rows of the tables correspond to the changed maximum moment: for the PAD1 program, M_{Max} = 2.582, for the PAD2 program, M_{Max} = 2.52.

Table 2.4a - Active resistance of the AMS replacement circuit

	R_1	$R_{2п}$	R_{2N}	R_{2c}	R_{12}	$\Delta P_{мех}$
PAD1	0,0486	0,0464	0,0455	0,0453	17,11	0,0686
PAD2	0,0340	0,0466	0,0462	0,0462	14,47	0,0249
PAD3	0,0521	0,0463	0,0454	0,0451	17,91	0,0196
PAD4	0,0521	0,0463	0,0453	0,0453	17,91	0,0196
PAD1	0,0521	0,0463	0,0454	0,0451	17,93	0,0196
PAD2	0,0521	0,0463	0,0454	0,0453	17,93	0,0196

When changing from M_{max} = 2.6 to M_{max} = 2.582, i.e. at 0.69%, the resistance R_1 in the calculations for the program PAD1 varies from R_1 = 0.0486 to R_1 = 0.0521, i.e. by 7.2%. The PAD2 program gives a change from R_1 = 0.034 to R_1 = 0.0521, i.e. by 53%, with a change in the maximum torque from M_{max} = 2.6 to M_{max} = 2.52, i.e. on 3,1%. Thus, the conclusion is confirmed that the programs PAD1 and PAD2, in view of the special sensitivity of their algorithms to the variation of the maximum moment, can not be recommended for calculating the parameters of the substitution circuit.

Table 2.4b - Inductive impedance of the AMS replacement circuit

	$x_{\sigma1}$	$x_{\sigma2п}$	$x_{\sigma2N}$	$x_{\sigma2c}$	x_{12}	$x''_{п}$
PAD1	0,0941	0,0868	0,1265	0,1429	1,99	0,1773
PAD2	0,0977	0,0901	0,135	0,1386	2,08	0,1841
PAD3	0,0932	0,0859	0,1262	0,143	1,98	0,1755
PAD4	0,0932	0,0859	0,1284	0,1318	1,98	0,1755
PAD1	0,0932	0,0859	0,1249	0,1409	1,97	0,1755
PAD2	0,0932	0,0859	0,1259	0,129	1,97	0,1758

The next engine is AMS5 with catalog data: Pnom =2,2 кВт; cos φ_N = 0,71; η_N = 0,765; s_N = 0,06; Iп = 4,0; Mп = 1,9; Mmax = 2,4. Table. 2.5a, b shows the parameters of the substitution circuit. The last two rows of the tables correspond to the changed maximum moment: for the PAD1 program, M_{max} = 2.413, for the PAD2 program, M_{max} = 2.362.

Table 2.5a- Active resistance of the AMS replacement circuit

	R_1	$R_{2п}$	R_{2N}	R_{2c}	R_{12}	$\Delta P_{мех}$
PAD1	0,0694	0,0805	0,0752	0,0753	17,75	0,0185
PAD2	0,0403	0,0815	0,0766	0,0762	12,58	0,027
PAD3	0,0573	0,081	0,0756	0,0738	15,08	0,022
PAD4	0,0573	0,081	0,0755	0,0751	15,08	0,022
PAD1	0,0573	0,081	0,0758	0,0741	15,1	0,022
PAD2	0,0385	0,0399	0,0291	0,0288	24,85	0,0146

Table 2.5b - Inductive impedance of the AMS replacement circuit

	$x_{\sigma1}$	$x_{\sigma2п}$	$x_{\sigma2N}$	$x_{\sigma2c}$	x_{12}	$x''_{п}$
PAD1	0,1085	0,1024	0,1825	0,2446	1,5	0,2044
PAD2	0,1175	0,1109	0,1978	0,2131	1,6	0,2213
PAD3	0,1126	0,1026	0,1966	0,2716	1,56	0,212
PAD4	0,1126	0,1062	0,2024	0,2219	1,57	0,2121
PAD1	0,1125	0,1062	0,1882	0,2510	1,55	0,2119
PAD2	0,1125	0,1062	0,1887	0,2032	1,54	0,212

From the analysis of the calculated data of Table. 2.5a, b on the parameters of the replacement circuit, the previous conclusions can be confirmed: the maximum torque equation can not be used to calculate the active resistance of the stator winding R_1, therefore the PAD1 and PAD2 programs can not be recommended for calculating the parameters of the ADC substitution circuit; the allowance for the displacement of the current in the rotor by expression (2.2) is more consistent with the general theory of current displacement; The PAD4 program is better suited for calculating static power loss characteristics.

The next AMS6 engine with catalog data: Pnom = 1.1 1,1 кВт; cos φ_N = 0,74; η_N = 0,74; s_N = 0,08; Iп = 4,0; Mп = 1,5; Mmax = 2,3. Table. 2.6a, b shows the parameters of the substitution circuit. The last two rows of the tables correspond to the changed maximum moment: for the PAD1 program, M_{max} = 2.2763, for the PAD2 program, M_{max} = 2.23.

Table 2.6a - Active resistance of the AMS replacement circuit

	R_1	$R_{2п}$	R_{2N}	R_{2c}	R_{12}	$\Delta P_{мех}$
PAD1	0,0596	0,0659	0,0971	0,1094	13,31	0,0249
PAD2	0,0452	0,0663	0,0981	0,1004	11,61	0,0291
PAD3	0,0678	0,0657	0,0963	0,1084	14,58	0,0225
PAD4	0,0678	0,0656	0,0962	0,0984	14,55	0,0225
PAD1	0,0678	0,0656	0,0965	0,1087	14,56	0,0225
PAD2	0,0678	0,0656	0,0965	0,0987	14,56	0,0225

Table 2.6b - Inductive impedance of the AMS replacement circuit

	$x_{\sigma 1}$	$x_{\sigma 2п}$	$x_{\sigma 2N}$	$x_{\sigma 2c}$	x_{12}	$x''_п$
PAD1	0,1163	0,1095	0,1827	0,2488	1,67	0,219
PAD2	0,1201	0,1113	0,1937	0,2124	1,74	0,2262
PAD3	0,1137	0,1072	0,1856	0,2606	1,65	0,2145
PAD4	0,01139	0,1071	0,1898	0,2104	1,66	0,2148
PAD1	0,1139	0,1072	0,1786	0,2422	1,64	0,2145
PAD2	0,1139	0,1072	0,1805	0,197	1,64	0,2145

The last of the considered engines AMS7 with catalog data: Pnom = 0,3 кВт; cos φ_N = 0,62; η_N =0,736; s_N=0,057; Il=3,5; Ml=2; Mmax=2,3.Table. 2.7a, b shows the parameters of the substitution circuit. The last two rows of the tables correspond to the changed maximum moment: for the program PAD1 M_{max} = 2,3409, for the program PAD2 M_{max} = 2,2773

Table 2.7a - Active resistance of the AMS replacement circuit

	R_1	$R_{2п}$	R_{2N}	R_{2c}	R_{12}	$\Delta P_{мех}$
PAD1	0,1342	0,0978	0,0809	0,0772	522,85	0,0006
PAD2	0,0645	0,0983	0,0807	0,0795	15,05	0,0211
PAD3	0,0887	0,0964	0,0797	0,0745	22,25	0,014
PAD4	0,0887	0,0962	0,0794	0,0783	22,25	0,014
PAD1	0,0887	0,0968	0,0803	0,0752	22,22	0,014
PAD2	0,0887	0,0967	0,0804	0,0793	22,3	0,0139

Table 2.7b - Inductive impedance of the AMS replacement circuit

	$x_{\sigma 1}$	$x_{\sigma 2п}$	$x_{\sigma 2N}$	$x_{\sigma 2c}$	x_{12}	$x''_{п}$
PAD1	0,0979	0,0928	0,2421	0,4836	1,17	0,1844
PAD2	0,1279	0,1236	0,2522	0,2804	1,31	0,2408
PAD3	0,1195	0,115	0,2775	0,4987	1,28	0,225
PAD4	0,1195	0,115	0,2873	0,3476	1,29	0,225
PAD1	0,1195	0,1152	0,2471	0,3855	1,25	0,225
PAD2	0,1194	0,1151	0,2435	0,2740	1,25	0,2248

Analysis of data on the parameters of the replacement schemes of the last two AMSs completely confirm the conclusions drawn from previous engines. These conclusions are as follows:

1. The maximum torque equation can not be used to determine the active resistance of the stator winding R_1 due to the special sensitivity of this resistance to the variations of the maximum moment. For AMSs of each type, the permissible deviation of the real value of the maximum torque from the catalog value is ± 10 %. With such permissible deviations M_{max}, the deviation of the resistance values R_1 can go beyond the allowed limits. Therefore, the programs PAD1 and PAD2, using this algorithm for calculating the resistance R_1, can not be used to calculate the parameters of the AMS substitution circuits.

2. Among two considered ways of taking current displacement in the winding of the AMS rotor, based on the expressions (2.1) and (2.2), the method using expression (2.2) is more appropriate. This method provides a minimum change in the parameters of the rotor winding in the working slip range from s = 0 to s = s_N, which corresponds to the conclusions of a more general theory of current displacement.

3. For calculating the parameters of the AMS replacement circuits with the aim of further calculating the static power loss characteristics, the PAD4 program should be recommended.

2.3 Features of the determination parameters of the replacement schemes of high-voltage AMSs

The basic design formulas for determining the parameters of the substitution circuit and the starting characteristics of high-voltage AMSs are given in Eqs. (2.20) - (2.56). The exception for high-voltage motors is the loss in the stator winding, which is defined as 0.4 i.e. from the total losses of active power in the nominal mode, therefore for these engines the expression (2.48) has the form:

$$R_1 = 0{,}4 \cdot (1-\eta_N) \cdot \eta_N \cdot \cos\varphi_N . \qquad (2.57)$$

According to the algorithm described above, a computer program was developed to calculate the parameters of the AMS substitution circuits. Based on the obtained parameters of the replacement circuit, calculation and construction of the starting characteristics of the engines is carried out.

In Table. 2.8, 2.9. Calculations of the parameters of the AMS substitution circuits according to the developed program are presented, including the initial (catalog) data of the motors themselves.

Table 2.8 - Catalog data of the AMS

№ motor.	Type	P_N, kW	U_N, V	$s_{a,N}$, %	η_N, %	$\cos\varphi_N$	Starting characteristics		
							$\frac{I_l}{I_N}$	$\frac{M_l}{M_N}$	$\frac{M_M}{M_N}$
1	ATD-1600	1600	6000	0,8	95,6	0,91	5,5	0,7	2,5
2	ATD-5000	5000	6000	0,5	96,5	0,91	5,6	0,7	2,4

Table 2.9 - Calculated parameters of the substitution circuit

№ motor	Type	R_1	$X_{\sigma1}$	R_{12}	X_{12}	R_{2l}	R_{2c}	$X_{\sigma2п}$	$X_{\sigma2c}$	$\Delta P_{мех}$
1	ATD-1600	0,0153	0,0944	73	3,78	0,0214	0,00792	0,0856	0,0939	0,0053
2	ATD-5000	0,0123	0,0931	85,9	3,77	0,0208	0,00488	0,0844	0,0921	0,00454

2.4 Static power loss characteristics in AMS

The conversion of electrical energy into mechanical in an asynchronous motor, as in other electric machines, is associated with energy losses, so the useful power at the output of the motor P2 is always less than the power input (power consumption) P1 by the loss amount with ∑P [33]:

$$P_2=P_1-\sum P \tag{2.58}$$

Losses of ∑P are converted to heat, which ultimately leads to heating of the machine. Losses in electric cars are divided into basic and additional. The main losses include magnetic, electrical and mechanical losses.

Losses of active power in asynchronous motors are divided into losses in the stator windings ΔP1, rotor ΔP2 and loss in steel of magnetic systems $\Delta P_{ст}$

$$\Delta P_m = \Delta P_1 + \Delta P_2 + \Delta P_{st}. \tag{2.59}$$

The power losses in the load motors are practically no different from the losses in the elements of the electrical network and therefore must be taken into account in the static power loss characteristics. It should also be remembered that load losses (including losses in engine windings) and losses in steel are significantly different depending on the voltage at the load node. The first ($\Delta P_н$) are determined by the relation

$$\Delta P_n \cong \frac{P^2(U)+Q^2(U)}{U^2} R, \tag{2.60}$$

where P (U) and Q (U) are the active and reactive powers transmitted through the element with resistance R, which increase with decreasing voltage. The second (**Δ**P_{st}) are defined by the relation

$$\Delta P_{st} \cong \frac{U^2}{R_м(U)}, \tag{2.61}$$

where $R_м$ – the active resistance of the magnetization branch and decrease with decreasing voltage.

From the ratio of these types of power losses, which are ultimately determined by the load factors of electric motors, the kind of static power loss characteristics essentially depends.

For the study of static characteristics, power losses are considered using asynchronous motors. The graphs of statistical characteristics of losses of active and reactive power of high-voltage and low-voltage AM arrays are constructed.

Figure 2.2 shows the static characteristics of the total losses of active power in a high-voltage asynchronous motor 5000 (P_{nom}=5000 kW) with load factors (Ks) from 0.5 to 1. The following designations are used: $\Delta P_{\Sigma AM}$(Kl=1) - total losses active power in AD with load factor 1; $\Delta P_{\Sigma AM}$(Kl=0,9) - the total losses of active power in AD at the load factor 0,9 etc .

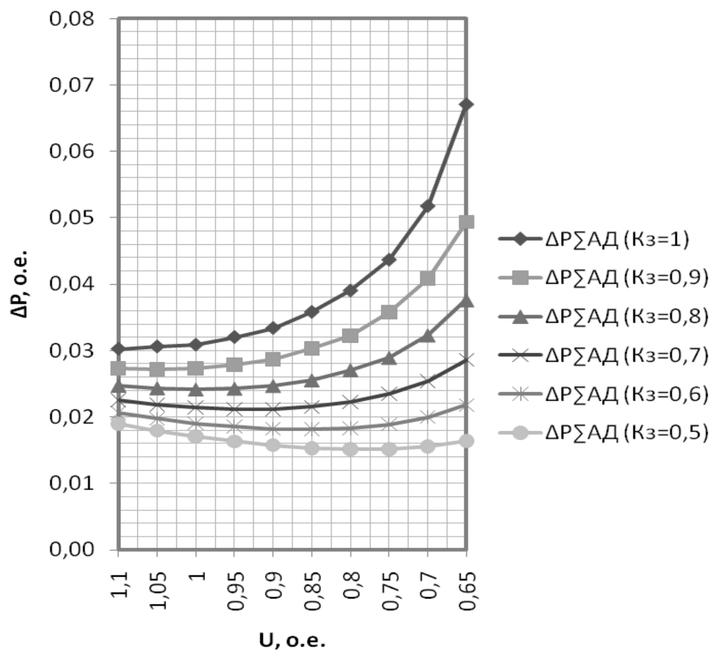


Figure 2.2 - Static characteristics of active power losses in the AMS-5000 at various load factors

Figure 2.3 presents the static characteristics of the total losses of active power in a high-voltage asynchronous motor AMS-1600 (P_n = 1600 kW) with load factors (Ks) from 0.5 to 1

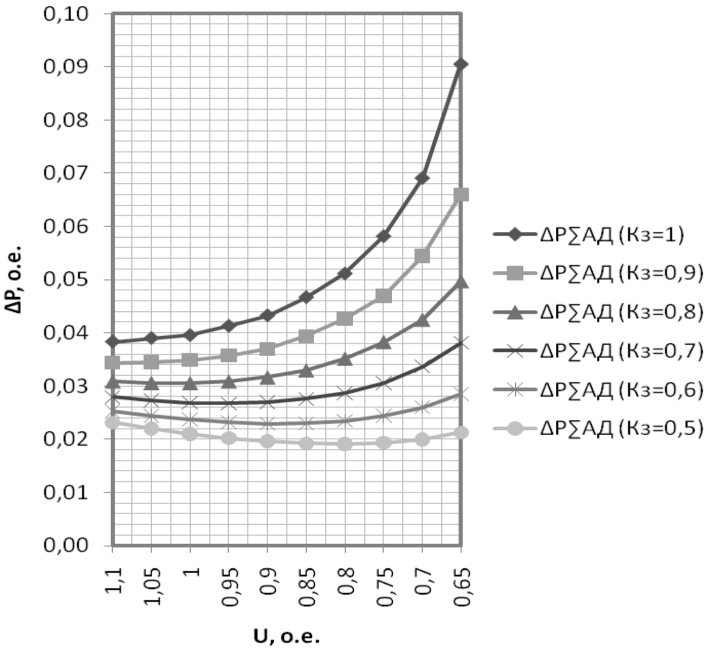


Figure 2.3 - Static characteristics of active power losses in the ATD-1600 at various load factors

Figure 2.4 shows the static characteristics of the total losses of active power in a low-voltage asynchronous motor A-52-2 (P_{nom} = 10 kW) with load factors (Ks) from 0.5 to 1

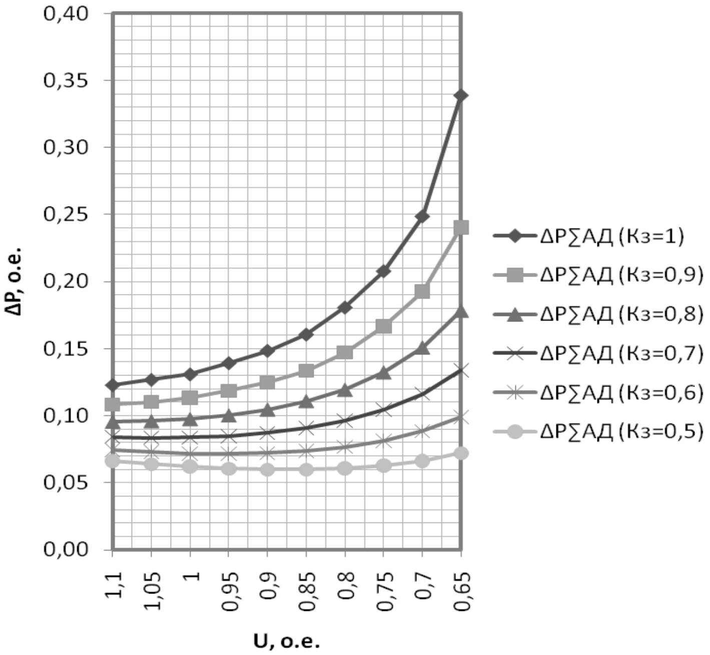


Figure 2.4 - Static characteristics of active power losses in A-52-2 for different load factors

Figure 2.5 presents the static characteristics of the total losses of active power in the low-voltage asynchronous motor AO-112-6 (P_{nom} = 250 kW) with load factors (Ks) from 0.5 to 1.

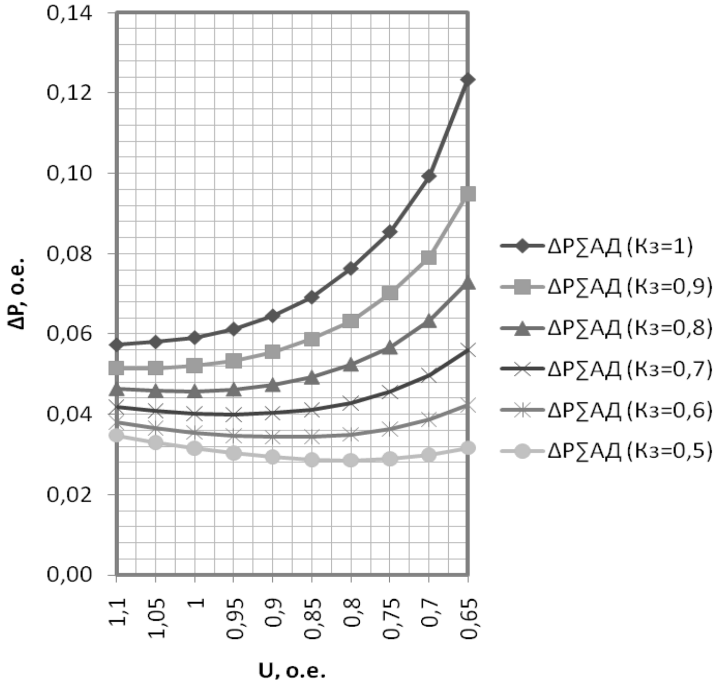


Figure 2.5 - Static characteristics of active power losses in AO-112-6 at different load factors

Figure 2.6 presents the static characteristics of reactive power consumption in a high-voltage asynchronous ATD-5000 engine with load factors (K_3) from 0.5 to 1. The following designations are used: $\Delta Q_{\Sigma AM}$(Kl=1) - consumption of reactive power in AM at load factor 1 etc.

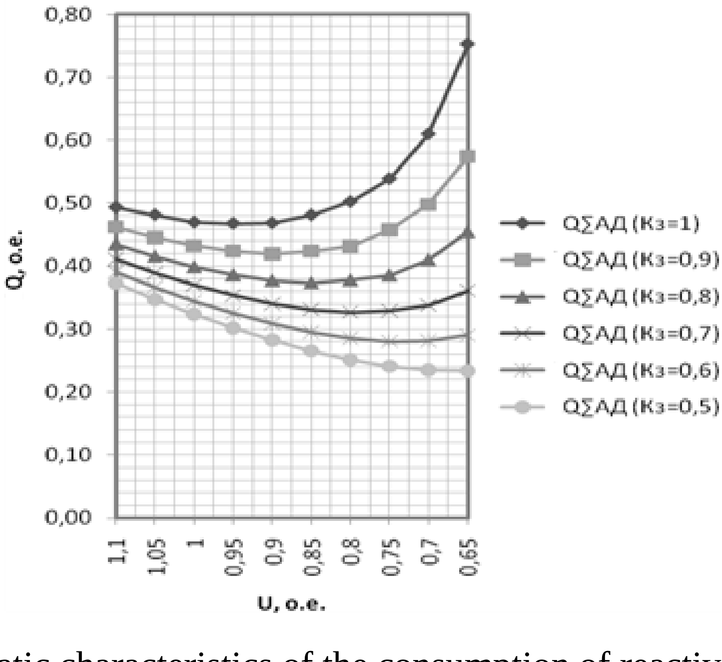


Figure 2.6 - Static characteristics of the consumption of reactive power in the AMS-5000 at various load factors

Figure 2.7 presents static characteristics of reactive power consumption in a high-voltage asynchronous AMS-1600 engine with load factors (Kl) from 0.5 to 1

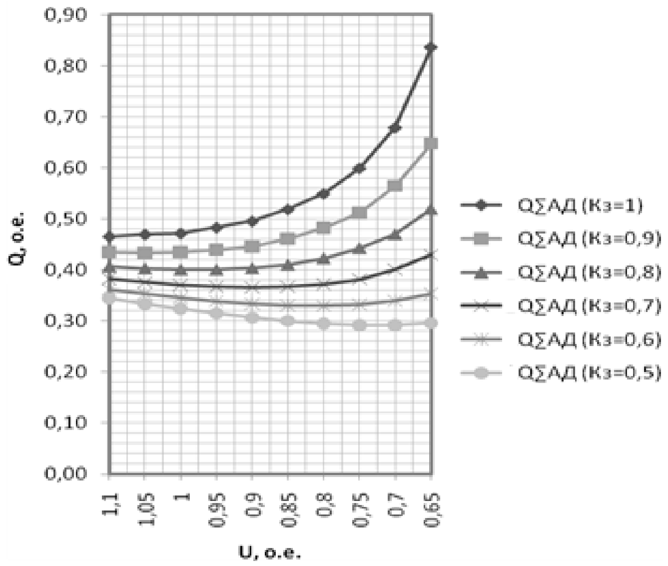


Figure 2.7 - Static characteristics of consumption of reactive power in the AMS-1600 at various load factors

Figure 2.8 presents static characteristics of consumption of reactive power in a low-voltage asynchronous motor A-52-2 with load factors (Kl) from 0.5 to 1.

Figure 2.9 shows the static characteristics of the consumption of reactive power in the low-voltage asynchronous motor AO-112-6 at the load factors (Kl) from 0.5 to 1

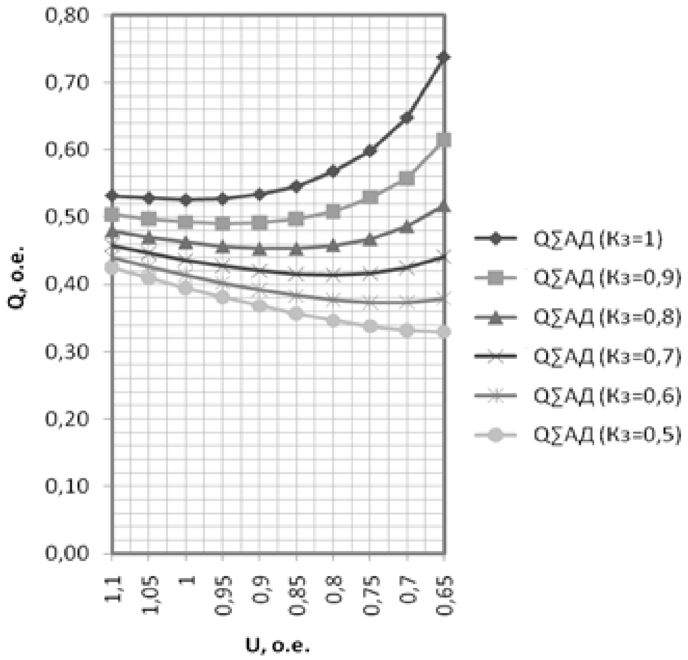


Figure 2.9 - Static characteristics of consumption of reactive power in AO-112-6 at different load factors

At the nominal voltage at the terminals, the asynchronous motor, working with full load, consumes active and reactive power from the network. In case of changing the mains voltage, the active power on the motor shaft remains practically constant, only the losses of active power in the engine change.

Analysis of the dependence of the change in the value of active and reactive losses for various types of motors on the voltage at their terminals shows that the most significant effect is the value of the load factor of the engine.

It is established that the common for the considered engines is an increase in the consumed reactive power with an increase in the applied voltage.

In addition, the specific consumption of reactive power increases with decreasing load factor.

When the voltage at the motor terminals changes, the slip changes, and consequently the speed of rotation.

When the voltage drops, the engine speed decreaPSS noticeably, especially for smaller engines. Conversely, increasing the voltage leads to an increase in the speed of the motors.

When running engines with low load factors, the change in voltage affects the motor speed very little.

When evaluating the effect of voltage changes on the economy of operation of induction motors, the cost of additional power losses caused by voltage deviation, the increase in reactive power consumed by the engine, and the change in economic indicators associated with the effect of rotation speed change on the performance of the corresponding mechanisms should be taken into account.

At present, there is no uniform methodology for estimating the economics of operation of induction motors.

At the same time, there is evidence that a correct asPSSsment of the effect of voltage changes on the economy of the operation of induction motors in a number of caPSS makes it possible to obtain a significant effect.

If the effect of the engine speed on the performance of the mechanisms takes place, then the voltage at the motor terminals must be maintained at least rated at low load factors, and within the maximum permissible value for large load factors (close to nominal).

In the absence of the effect of the engine speed on the performance of the mechanisms, it is advisable to maintain the voltage at the motor terminals not higher than the rated voltage for large load factors and below the nominal load factor for small load factors.

2.5 Conclusions on the chapter

1. The methodology, algorithm and program for calculating the parameters of the replacement circuit and starting characteristics, high-voltage AMS with respect to the determination of the static characteristics of power losses are developed.

2. The methodology, algorithm and program for calculating the parameters of the replacement circuit and starting characteristics, low-voltage AMS with respect to the

determination of the static characteristics of power losses are developed.

3. Of the two considered ways of taking into account the current displacement in the winding of the AMS rotor, based on the expressions (2.1) and (2.2), the method using expression (2.2) is more appropriate. This method ensures a minimum change in the parameters of the rotor winding in the working slip range from s = 0 to $s = s_N$, which corresponds to the conclusions of a more general theory of current displacement;

4. The voltage at the AMS terminals, at which the minimum of the total active power losses is ensured, depends significantly on the load factor and changes when the load factor varies from 1 to 0.5, in the range from 1.1 to 0.75 of the nominal one.

5. The voltage at the terminals of the AMS, at which the minimum of the total losses of reactive power is ensured, depend significantly on the load factor and change when the load factor varies from 1 to 0.5, in the range from 1.1 to 0.65 of the nominal.

3 PARAMETERS DETERMINATION AND CHARACTERISTICS OF SYNCHRONOUS ENGINES WITH SHIELD POLES AND A MASSIVE SMOOTH ROTOR

Synchronous motors are widely used in the industry for electric drives operating at a constant speed. You can find synchronous motors which are used as a drive for large-capacity pumps of long-term operation. The synchronous motor has several advantages over asynchronous motor: high power factor cosφ = 0,9; the possibility of using synchronous motors in enterpriPSS to increase the overall power factor; high efficiency (more than for an asynchronous motor at (0.5-3)%, this is achieved by decreasing losses in copper and large cosφ); the torque of the synchronous motor is directly proportional to the voltage in the first degree, i.e. the synchronous motor will be less sensitive to the change in the magnitude of the mains voltage.

3.1 Calculation of the parameters and characteristics of synchronous motors with shield poles

Synchronous motors with shield poles (SMSP) are the most common type of pole SM with a rotation speed $n_{ном} \leq$ 1000 rpm. These include synchronous motors series SD, VDN, SDV, KFOR (and several others), used as drives of various industrial mechanisms (pumps, fans, mills, mixers, etc.). The start of the SMSP is, as a rule, carried out from the full mains voltage during the excitation winding, closed for additional starting resistance.

Parameters of SM are conveniently expressed in relative units, when the following are accepted as basic conditions: $S_Б = S_N$ - nominal total power of the SM; $U_Б = U_N$ - rated voltage of the SM. The exception is the electromagnetic moment, which is expedient to express in fractions of the nominal motor torque.

Schemes of substitution of the SMSP for longitudinal (a) and transverse (b) axes are shown in Figure 3.1.

The parameters of the substitution scheme are: R_{ad}, R_{aq}, $R_{ст}$, R_f, R_{1d}, R_{1q} respectively are the resistances of the magnetization branch along the longitudinal and transverse axes of the rotor, stator winding, excitation windings and damper windings along the longitudinal and transverse axes of the rotor; X_{ad}, X_{aq}– resistances of mutual inductance between stator and rotor windings along the d and q axes, and, respectively, inductive resistances of scattering of the stator winding, excitation windings and damper windings along the axes d and q;, X_{σ} $X_{\sigma f}$, $X_{\sigma 1d}$, $X_{\sigma 1q}$; $R_{fп}$ is the resistance of the excitation winding when the SM starts, when the field windings are closed to an additional starting resistance $R_п$ ($R_{fп} = R_f + R_п$). Coefficient of the frequency of the starting resistance with respect to the winding resistance.

For the SM with polished poles, the following expression holds

$$R_{ad} = R_{aq}. \tag{3.1}$$

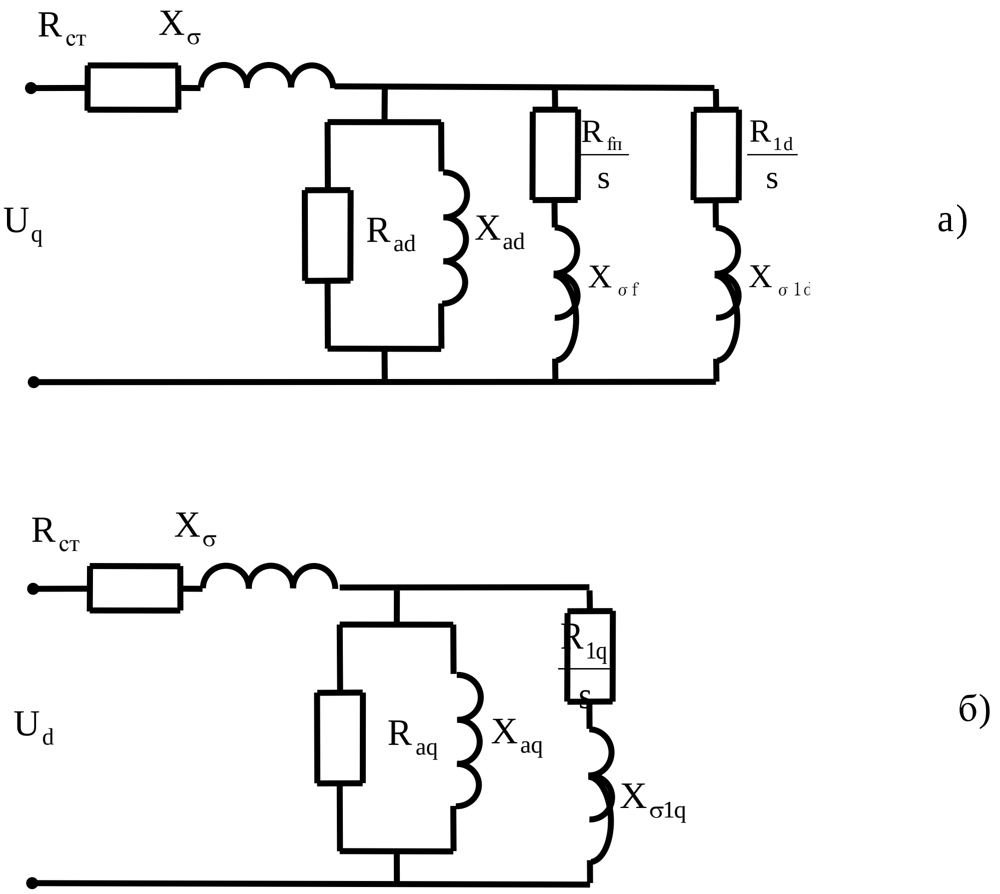


Figure 3.1 - Schemes of substitution along the longitudinal (a) and transverse (b) axes of the SMSP

Based on the parameters of the substitution scheme, generalized parameters and parameters of the SM mode can be determined. The general parameters of the SM are: synchronous inductive resistances along the longitudinal and transverse axes of the rotor:

$$X_d = X_\sigma + X_{ad},$$
$$X_q = X_\sigma + X_{aq}; \tag{3.2}$$

supertransitive inductive resistances along the d and q axes:

$$X''_d = X_\sigma + \left(\frac{1}{X_{ad}} + \frac{1}{X_{\sigma f}} + \frac{1}{X_{\sigma 1d}} \right)^{-1},$$
$$X''_q = X_\sigma + \left(\frac{1}{X_{aq}} + \frac{1}{X_{\sigma 1q}} \right)^{-1}; \tag{3.3}$$

transient inductive resistance along the longitudinal axis (in the absence of a damper winding)

$$X'_{d0} = X_{\sigma} + \left(\frac{1}{X_{ad}} + \frac{1}{X_{\sigma f}} \right)^{-1}; \tag{3.4}$$

inductive resistance of the excitation winding and damper windings along the d and q axes with the open stator winding

$$\begin{aligned} X_f &= X_{\sigma f} + X_{ad}, \\ X_{1d} &= X_{\sigma 1d} + X_{ad}, \\ X_{1q} &= X_{\sigma 1q} + X_{aq}; \end{aligned} \tag{3.5}$$

Inductive resistance of the same windings, but with a short-circuited stator winding

$$\begin{aligned} X'_f &= X_{\sigma f} + X'_{ad}, \\ X'_{1d} &= X_{\sigma 1d} + X'_{ad}, \\ X'_{1q} &= X_{\sigma 1q} + X'_{aq}; \end{aligned} \tag{3.6}$$

where X'_{ad}, X'_{aq} – equivalent resistance of mutual induction between stator and rotor windings with a short-circuited stator winding, equal to

$$\begin{aligned} X'_{ad} &= \frac{X_{ad} \cdot X_{\sigma}}{X_{ad} + X_{\sigma}}, \\ X'_{aq} &= \frac{X_{aq} \cdot X_{\sigma}}{X_{aq} + X_{\sigma}}; \end{aligned} \tag{3.7}$$

constants time of the excitation winding with an open and short-circuited stator winding

$$\begin{aligned} T_{f0} &= \frac{X_f}{R_f}, \\ T'_f &= \frac{X'_f}{R_f}; \end{aligned} \tag{3.8}$$

constants time of damper windings along the longitudinal and transverse axes with an open and short-circuited stator winding

$$T_{1d0} = \frac{X_{1d}}{R_{1d}},$$
$$T_{1q0} = \frac{X_{1q}}{R_{1q}},$$
$$T'_{1d} = \frac{X'_{1d}}{R_{1d}}, \tag{3.9}$$
$$T'_{1q} = \frac{X'_{1q}}{R_{1q}}.$$

constants time of transient and supertransient procesPSS along the longitudinal axis of the rotor with an open stator winding, determined by the system of equations

$$\begin{gathered} T'_{d0}\, T''_{d0} = \sigma_0 T_{f0} T_{1d0}; \\ T'_{d0} + T''_{d0} = T_{f0} + T_{1d0}, \end{gathered} \tag{3.10}$$

where σ_0 – the total coefficient of scattering of the excitation winding and the damper winding along the longitudinal axis with the open stator winding

$$\sigma_0 = 1 - \frac{X_{ad}^2}{X_f \cdot X_{1d}}; \tag{3.11}$$

constants time of the transient and supertransient procesPSS along the longitudinal axis of the rotor with a short-circuited stator winding are determined

$$\begin{gathered} T'_d\, T''_d = \sigma' \cdot T'_f\, T'_{1d}; \\ T'_d + T''_d = T'_f + T'_{1d}, \end{gathered} \tag{3.12}$$

where σ' – the total coefficient of scattering of the excitation winding and longitudinal damper winding with a short-circuited stator winding

$$\sigma' = 1 - \frac{(X'_{ad})^2}{X'_f \cdot X'_{1d}}. \tag{3.13}$$

For the transition resistance of SMs, taking into account the damper winding and supertransition resistances, the following relationships are valid:

$$
\begin{aligned}
X'_d &= X_d\,\frac{T'_f + T'_{1d}}{T_{f0} + T_{1d0}} = X_d\,\frac{T'_d + T''_d}{T'_{d0} + T''_{d0}},\\
X''_d &= X_d\,\frac{\sigma' T'_f\,T'_{1d}}{\sigma_0 T_{f0} T_{1d0}} = X_d\,\frac{T'_d\,T''_d}{T'_{d0}\,T''_{d0}},\\
X''_q &= X_q\,\frac{T'_{1q}}{T_{1q0}}.
\end{aligned}
\tag{3.14}
$$

Parameters of start-up of SM are: active and reactive power consumed by the motor from the network, the current of the stator winding and the moment

$$
\begin{aligned}
P &= \frac{U^2}{2}\cdot \operatorname{Re}\left(\frac{1}{\underline{Z}_d(s)} + \frac{1}{\underline{Z}_q(s)}\right);\\
Q &= \frac{U^2}{2}\cdot \operatorname{Im}\left(\frac{1}{\underline{Z}_d(s)} + \frac{1}{\underline{Z}_q(s)}\right);\\
I &= \frac{U}{2}\cdot \left|\frac{1}{\underline{Z}_d(s)} + \frac{1}{\underline{Z}_q(s)}\right|;\\
M &= \frac{S_N}{P_N}\left(P - I^2\cdot R_{\text{ст}} - U_{ad}^2/R_{ad}\right);
\end{aligned}
\tag{3.15}
$$

where $Z_d(S)$ и $Z_q(S)$ – equivalent complex (conjugate) resistances, along the longitudinal and transverse axes in asynchronous mode with slip s in accordance with the substitution scheme (Figure 2.1), equal to

$$
\begin{aligned}
\underline{Z}_d(s) &= R_{\text{ст}} + jX_\sigma + \left(\frac{1}{R_{ad}} + \frac{1}{jX_{ad}} + \frac{1}{\frac{R_{f\text{п}}}{s} + jX_{\sigma f}} + \frac{1}{\frac{R_{1d}}{s} + jX_{\sigma 1d}}\right)^{-1},\\
\underline{Z}_q(s) &= R_{\text{ст}} + jX_\sigma + \left(\frac{1}{R_{ad}} + \frac{1}{jX_{aq}} + \frac{1}{\frac{R_{1q}}{s} + jX_{\sigma 1q}}\right)^{-1}.
\end{aligned}
\tag{3.16}
$$

Dependences from the slip of P(s), Q(s), I(s), M(s) at the rated voltage at the motor terminals are called the starting characteristics of the SM.

In the catalogs of the SM the following data are given: P_N - rated power on the motor shaft; U_N is the nominal voltage of the SM; $\cos\varphi_N$ – - rated power factor; - rated efficiency; $M_{\text{п}}$, $M_{\text{в}}$ is the multiplicity of the starting (for s = 1) and the input (for s = 0.05) asynchronous electromagnetic moments; M_M - the multiplicity of the maximum synchronous moment; I_n is the frequency of the starting current; U_{fN}, I_{fN} - rated voltage and current of the field winding.

Algorithm for calculating the parameters of the substitution scheme of the SMSP.

The main requirement for the algorithm is the correspondence of the calculated parameters of the circuit for replacing the SM by catalog data, i.e. mode parameters corresponding to the catalog data (for example, $M_п$, M_B, M_M, $I_п$), but calculated through the parameters of the replacement circuit, should be equal to this catalog data.

The active resistance of the stator winding in relative units is equal to the loss of active power in this winding in the nominal mode of the SM, which constitutes a stable fraction (on average 0.4) of the total active power loss in the SM

$$R_{ст} = 0{,}4 \cdot (1 - \eta_N) \cdot \eta_N \cdot \cos\varphi_N . \tag{3.17}$$

The basic design expression for determining the synchronous resistance X_d is the expression for the maximum synchronous moment

$$M_M \cdot \frac{P_N}{S_N} = P_M = \frac{E_{qN}}{X_d} \sin\delta_M + \frac{X_d - X_q}{2X_d X_q} \sin 2\delta_M , \tag{3.18}$$

where δ_M – the internal angle of the SM corresponding to the maximum synchronous moment and the maximum active power of the P_M in synchronous mode; S_N is the nominal total power of the SM, equal to

$$S_N = \frac{P_N}{\cos\varphi_N \cdot \eta_N} , \tag{3.19}$$

where E_{qN} – The nominal synchronous EMF, determined by the relation

$$E_{qN} = \sqrt{(1 + \sin\varphi_N \cdot X_d)^2 + (\cos\varphi_N \cdot X_d)^2} , \tag{3.20}$$

where X_q – the cross synchronous resistance of the pole SM which constitutes a relatively stable fraction (on average 0.6) of the resistance X_d, i.e.

$$X_q \approx 0{,}6 \cdot X_d . \tag{3.21}$$

From the expression (3.18), taking into account the relations (3.20), (3.21), an unsaturated value of the synchronous resistance X_d can be obtained:

$$X_d = \frac{0{,}18P_M + 1{,}318\sin\varphi_N - 0{,}326\cos\varphi_N}{1{,}073P_M^2 - 1} + \\ + \frac{\sqrt{(0{,}18P_M + 1{,}318\sin\varphi_N - 0{,}326\cos\varphi_N)^2 + 1{,}81(1{,}073P_M^2 - 1)}}{1{,}073P_M^2 - 1} \qquad (3.22)$$

The remaining parameters of the substitution scheme of the SMSP are determined by the method of successive approximations from the condition that the catalog and calculation data of the same name coincide. However, since the catalog data are substantially smaller than the parameters of the substitution scheme, the equations of successive approximations must be supplemented by a series of approximate relations characterizing the relatively stable properties of SD.

It is advisable to express X''_d the superconducting resistance in the form of an iterative ratio through the starting current

$$X''^{(i)}_d = X''^{(i-1)}_d \left(1 - \frac{\Delta I_п}{I_п}\right), \qquad (3.23)$$

where $X''^{(i)}_d$ и $X''^{(i-1)}_d$ – the resistance values X''_d at the i-th and (i-1) -th steps of the process of successive approximations; - the difference between the catalog and calculated values of the starting current at the next step of approximation

$$\Delta I_n = I_n - I_{n1}. \qquad (3.24)$$

The calculated value of the starting current I_{n1} is determined by the relations (3.15), (3.16) with slip s = 1.

In the absence of more reliable data on the resistance X''_q , X'_{d0} they can be calculated from the following approximate relationships:

$$\begin{aligned} X''_q &= 1{,}1 \cdot X''_d, \\ X'_{d0} &= 1{,}6 \cdot X''_d, \\ X_\sigma &= 0{,}6 \cdot X''_d. \end{aligned} \qquad (3.25)$$

The remaining inductive impedances of the SMSP substitution circuit can be calculated from the formulas following from (3.2) - (3.4):

$$
\begin{aligned}
X_{ad} &= X_d - X_\sigma, \\
X_{aq} &= X_q - X_\sigma, \\
X_{\sigma f} &= X_{ad}\frac{X'_{d0} - X_\sigma}{X_d - X'_{d0}}, \\
X_{\sigma 1q} &= X_{aq}\frac{X''_q - X_\sigma}{X_q - X''_q}, \\
X_{\sigma 1d} &= \frac{(X'_{d0} - X_\sigma)(X''_d - X_\sigma)}{X'_{d0} - X''_d}.
\end{aligned} \tag{3.26}
$$

The active resistances R_{1d} and $R_{f\text{п}}$ the substitution schemes of the SMSP are expediently expressed in the form of iterative relations through the starting and input moments:

$$
\begin{aligned}
R_{1d}^{(i)} &= R_{1d}^{(i-1)}\left(1 + \frac{\Delta M_\text{п}}{M_\text{п}}\right); \\
R_{f\text{п}}^{(i)} &= R_{f\text{п}}^{(i-1)}\left(1 + \frac{\Delta M_B}{M_B}\right),
\end{aligned} \tag{3.27}
$$

where $R_{1d}^{(i)}$, $R_{1d}^{(i-1)}$, $R_{fn}^{(i)}$, $R_{fn}^{(i-1)}$ – resistance values R_{1d} and R_{fn} at the i-th and (i-1) -th steps of the process of successive approximations; ΔM_{sa}, ΔM_B - the difference between the catalog and calculated values of the starting and input moments at the next step of successive approximations:

$$
\begin{aligned}
\Delta M_{ap} &= M_{ap} - M_{ap1}, \\
\Delta M_I &= M_I - M_{I1}.
\end{aligned} \tag{3.28}
$$

The calculated values of the starting $M_{\text{п}1}$ and input moments M_{B1} are determined from the relations (2.72), (2.73) for slides s = 1 and s = 0.05.

The active resistance of the transverse damper winding R_{1q} of the SMSP is a stable fraction of the resistance R_{1d}:

$$
R_{1q} = 0{,}71 \cdot R_{1d} \tag{3.29}
$$

The active resistance of the excitation winding Rf can be expressed in terms of the rated voltage U_{fN} and the field current of the field winding I_{fN}

$$R_f = 0{,}622 \cdot \frac{U_{fN} \cdot I_{fN}}{S_N} \left(\frac{X_{ad}}{X_d \cdot M_M(\frac{P_N}{S_N}) - 0{,}167} \right)^2 \quad (3.30)$$

The inductive resistance of the excitation winding can be determined through the parameters of the replacement circuit and the generalized parameters of the SM

$$X_f = \frac{X_{ad}^2}{X_d - X'_{d0}} \quad (3.31)$$

The active resistance of the magnetization branch can be determined from the following relations. The sum of the power losses in the steel $\Delta P_{ad.N}$ Pad.N and the mechanical power losses $\Delta P_{ad.N}$ in the nominal mode, which can be conditionally called the loss of idling power in the nominal mode □Px.N, is equal to

The active resistance of the magnetization branch can be determined from the following relations. The sum of the power losses in the steel $\Delta P_{ad.N}$ and the mechanical power losses $\Delta P_{мех.N}$ in the nominal mode, which can be conditionally called the loss of idling power in the nominal mode $\Delta P_{x.N}$ is equal to

$$\Delta P_{x.N} = \Delta P_{\Sigma N} - \Delta P_{1N} - \Delta P_B, \quad (3.32)$$

where

$$\Delta P_{\Sigma N} = (1 - \eta_N) \cos\varphi_N \quad (3.33)$$

total power losses in the nominal mode of the SM;$\Delta P_{1N} = R_1$ -

(3.34)

loss of power in the stator winding in the rated mode of the SM;

$$\Delta P_l = \frac{U_{fN} \cdot I_{fN}}{S_N} - \quad (3.35)$$

loss of power in the excitation winding in the nominal mode of the LED.

The mechanical power losses and power losses in the SD steel constitute a stable fraction of the losses $\Delta P_{x.N}$, on averageпотери мощности в обмотке возбуждения в номинальном режиме СД.

$$\left. \begin{aligned} \Delta P_{mech.N} &= 0{,}4 \Delta P_{x.N}, \\ \Delta P_{ad.N} &= 0{,}6 \Delta P_{x.N}. \end{aligned} \right\} \quad (3.36)$$

From the expressions (3.29) - (3.31) it follows that

$$\Delta P_{mech.N} = 0{,}4\left[(1-\eta_N)\cos\varphi_N - R_1 - \frac{U_{fN}\cdot I_{fN}}{S_N}\right], \tag{3.37}$$

$$\Delta P_{ad.N} = 0{,}6\left[(1-\eta_N)\cos\varphi_N - R_1 - \frac{U_{fN}\cdot I_{fN}}{S_N}\right], \tag{3.38}$$

$$R_{ad} = \frac{U_{ad.N}^2}{\Delta P_{ad.N}}. \tag{3.39}$$

The calculation of the parameters of the substitution scheme of the SMSP is carried out in the following sequence. For initial approaches of resistances were accepted X''_d, R_{1d}, $R_{f\pi}$

$$X''_d{}^{(0)} = \frac{1}{I_n}\sqrt{1-\left(\frac{I_n{}^2\cdot R_{st} + M_n\cdot\cos\varphi_N\cdot\eta_N}{I_n}\right)^2},$$

$$R_{1d}{}^{(0)} = \frac{M_l\cdot\cos\varphi_N\cdot\eta_N}{I_n{}^2}, \tag{3.40}$$

$$R_{f\pi}{}^{(0)} = 4\cdot R_f\ .$$

Then, using the expressions (3.25) - (3.29), the initial approximations of the remaining parameters of the replacement circuit are calculated X''_d. Further, the first approximations of the resistances R_{1d}, $R_{f\pi}$ are calculated from expressions (3.23), (2.26), and calculations by the method of successive approximations are repeated until condition

$$\left|\frac{\Delta I_n}{I_n}\right| + \left|\frac{\Delta M_n}{M_n}\right| + \left|\frac{\Delta M_B}{M_B}\right| < \varepsilon, \tag{3.41}$$

where $\varepsilon = 0{,}001$ – given accuracy of calculations by the method of successive approximations. After the condition (3.41) is satisfied, the parameters obtained at the last step of the iterative calculation are taken as the calculated parameters of the SMSP substitution scheme. The generalized parameters and starting characteristics of the SM are calculated from (3.5) - (3.15) after determining the parameters of the substitution circuit.

In Table 3.1, 3.2, the catalog data and calculated parameters of the SM replacement circuits obtained using this algorithm are given.

Table 3.1 - Catalog data

Type of motor	P_N, kW	U_N, k	$\cos\varphi_N$	η_N, %	Starting characteristics				Data on the field winding	
					$\frac{I_п}{I_н}$	$\frac{M_п}{M_н}$	$\frac{M_B}{M_н}$	$\frac{M_M}{M_н}$	$U_{fн}$, B	$I_{fн}$, A
CDH-16-64-6	5000	6	0,9	96,8	6,8	0,95	1,8	2,1	108	285
CDH-16-104-6	6300	6	0,9	97,1	6,8	0,95	1,8	2,0	113	280
CDH-17-94-8	8000	6	0,9	97,1	6,5	0,85	1,6	2,0	132	350
CDH-17-119-8	10000	6	0,9	97,3	6,8	0,9	1,6	2,0	177	300
CDH-18-71-10	8000	6	0,9	96,8	6,5	0,95	1,7	2,0	169	285
CDH-18-91-10	10000	6	0,9	97,2	6,9	1,0	1,6	2,0	178	280
СД2-74/25-604	225	0,38	0,9	93,8	5,5	0,95	1,1	1,7	146	265

Table 3.2 - Calculated parameters of the substitution circuit

Type	$R_{ст}$	R_f	K_p	R_{1d}	R_{1q}	X_σ	X_{ad}	X_{aq}	$X_{\sigma f}$	$X_{\sigma 1d}$	$X_{\sigma 1q}$
CDH-16-64-6	0,0115	0,00102	4,49	0,0395	0,0281	0,0816	1,02	0,581	0,157	0,0907	0,077
CDH-16-104-6	0,0104	0,000916	4,69	0,0392	0,0278	0,0817	1,11	0,633	0,155	0,0908	0,0763
CDH-17-94-8	0,0104	0,00105	2,89	0,0388	0,0275	0,0858	1,1	0,629	0,164	0,0953	0,0807
CDH-17-119-8	0,00972	0,000966	2,41	0,0375	0,0266	0,082	1,1	0,63	0,156	0,0911	0,0766
CDH-18-71-10	0,0115	0,0011	4,24	0,0431	0,0306	0,0853	1,11	0,633	0,163	0,0947	0,08
CDH-18-91-10	0,0101	0,000911	2,86	0,0403	0,0286	0,0804	1,11	0,633	0,152	0,0893	0,0749
СД2-74/25-604	0,0223	0,00405	0,374	0,0573	0,047	0,0987	1,65	0,95	0,183	0,11	0,09

3.2 Calculation of parameters and characteristics of synchronous motors with a massive smooth rotor

Synchronous motors with a massive smooth rotor (SDMR) include non-polar SM with a rotor speed of 3000 rpm (STM series, STD). The rotor SDMR is a single steel forging with milled grooves for the excitation winding. In SDMR, the system of damper circuits is distributed throughout the barrel of the rotor.

SDMR are used as drives to centrifugal pumps, compressors and fans. The start of the SIDM is carried out mainly from the full (sometimes reduced) network voltage with a short-circuited excitation winding.

The replacement schemes of the SDMR along the longitudinal (a) and transverse (b) axes of the rotor are similar to those shown in Fig. 3.1.

In contrast to SMs with a bonded rotor, SDMR are characterized by the following features.

1. In connection with the symmetry of the rotor along the longitudinal (d) and transverse (q) axes, the following relationships hold:

$$\begin{aligned} & X_d = X_q, \\ & X_{ad} = X_{aq}, \\ & X_{\sigma 1d} = X_{\sigma 1q} = X_{\sigma 1}, \\ & R_{1d} = R_{1q} = R_1, \\ & R_{ad} = R_{aq}. \end{aligned} \tag{3.42}$$

2. 2. In the massive rotor of the SDMR, it is necessary to take into account the current displacement in the damper circuits of the rotor. The degree of displacement mainly depends on the frequency of the currents induced in the rotor, i.e. ultimately from slipping the engine. The effect of current displacement $X_{\sigma 1}$ leads to a change in the active R_1 and the inductive resistance of the scattering of an equivalent damper circuit as a function of the slip of the rotor.

The changes in the resistances of an equivalent damping circuit are determined by the following dependences, which follow from the theory of a massive rotor:

$$R_1(s) = \sqrt{R_{1c}^2 + \left(R_{1п}^2 - R_{1c}^2\right)s}\ , \tag{3.43}$$

$$X_{\sigma 1}(s) = \frac{X_{\sigma 1c} X_{\sigma 1п}}{\sqrt{X_{\sigma 1п}^2 + \left(X_{\sigma 1c}^2 - X_{\sigma 1п}^2\right)s}}, \tag{3.44}$$

where $R_{1п}$, $X_{\sigma 1п}$, R_{1c}, $X_{\sigma 1c}$ – active and inductive damping resistance of the damper circuit, respectively, when starting (s = 1) and in synchronous mode (s = 0).

3. Due to the fact that the resistances $R_1(s)$ and $X_{\sigma 1}(s)$ and the equivalent damper circuit depend on the slip, then the generalized parameters of the SDMR, in the calculation expressions for which the resistors сопротивления $R_1(s)$ and $X_{\sigma 1}(s)$ and also depend on the slip.

In particular, they depend on sliding X''_d and X''_q supertransitive resistances both along the longitudinal and transverse axes active and inductive damping resistance of the damper circuit, respectively, when starting (s = 1) and in synchronous mode (s = 0).

$$X''_d = X_\sigma + \left(\frac{1}{X_{ad}} + \frac{1}{X_{\sigma f}} + \frac{1}{X_{\sigma 1}(s)} \right)^{-1}, \qquad (3.45)$$

$$X''_q = X_\sigma + \left(\frac{1}{X_{ad}} + \frac{1}{X_{\sigma 1}(s)} \right)^{-1}. \qquad (3.46)$$

electromagnetic constants of an equivalent damper circuit along the longitudinal and transverse axes with a short-circuited stator winding

$$T'_{1d} = T'_{1q} = T'_{1d} = \frac{R_1(s)}{X_{\sigma 1}(s) + \frac{X_\sigma \cdot X_{ad}}{X_\sigma + X_{ad}}}. \qquad (3.47)$$

electromagnetic constants of the transient and supertransient procesPSS with a short-circuited stator winding.

Parameters of the mode when starting the SM are: active P and reactive Q power consumed by the motor from the network, stator winding current I and electromagnetic moment. They are determined by expressions (3.15).

The algorithm for calculating the parameters of the replacement circuit of the SDMR is implemented as follows. The unsaturated value of the synchronous resistance is defined as

The algorithm for calculating the parameters of the replacement circuit of the SDMR is implemented as follows. The unsaturated value of the synchronous resistance is defined as

$$X_d = \frac{1{,}13}{\cos\varphi_N \cdot \sqrt{P_M^2 - 1} - \sin\varphi_N}. \qquad (3.48)$$

The remaining parameters of the replacement circuit of the SDMR are determined by the method of successive approximations $X_{\sigma 1п}$ from the condition that the catalog and calculation data of the same name coincide.

The inductive resistance of dissipation of an equivalent damper circuit in the starting mode constitutes a stable fraction (on average 0.55) of the active resistance R_{1n} (this follows from the theory of a massive rotor), therefore

$$X_{\sigma 1п} \approx 0{,}55 \cdot R_{1п}. \qquad (3.49)$$

Inductive resistance of stator winding scattering

$$X_\sigma = 1{,}3 \cdot X''_{dп} - \sqrt{0{,}09 \cdot (X''_{dп})^2 + 0{,}6 \cdot X''_{dп} \cdot X_{\sigma 1п}}. \qquad (3.50)$$

The active resistance of the excitation winding R_f can be expressed in terms of the rated voltage UfN and the field current I_{fN} of the field winding
The active resistance of the R_f excitation winding can be expressed in terms of the UfN rated voltage and I_{fN} fiels windings.

$$R_f = 0{,}667 \cdot \frac{U_{fN} \cdot I_{fN}}{P_N \cos\varphi_N \cdot \eta_N} \left(\frac{X_{ad}}{X_d \cdot M_M} \right)^2 . \tag{3.51}$$

The mechanical power losses and power losses in the steel are determined as well as for the SDMS.

The calculation of the parameters of the replacement circuit of the SDMR is carried out in the following order. For initial approaches of resistances $X''_{dп}$, $R_{1п}$, R_{1c} are taken.

$$\begin{gathered} X''^{(0)}_{dn} = \frac{1}{I_n} \sqrt{1 - \left(\frac{I_n^{\ 2} \cdot R_{st} + M_l \cdot \cos\varphi_N \cdot \eta_N}{Il} \right)^2} , \\ R_{1п}^{(0)} = 1{,}2 \cdot \frac{M_п \cdot \cos\varphi_N \cdot \eta_N}{I_п^{\ 2}} , \\ R_{1c}^{(0)} = 0{,}4 \cdot R_{1п}^{(0)} . \end{gathered} \tag{3.52}$$

then, according to expressions (3.25) - (3.29), the first approximations of the resistances $X''_{dп}$, $R_{1п}$, R_{1c} are calculated, and calculations by the method of successive approximations are repeated until condition

$$\left| \frac{\Delta I_п}{I_п} \right| + \left| \frac{\Delta M_п}{M_п} \right| + \left| \frac{\Delta M_B}{M_B} \right| < \varepsilon , \tag{3.53}$$

where $\varepsilon = 0{,}001$ – given accuracy of calculations by the method of successive approximations.

After the condition (3.53) is satisfied, the parameters obtained at the last step of the iterative calculation are taken as the calculated parameters of the replacement circuit of the SDMR. The generalized parameters and starting characteristics of the SDMR are calculated after determining the parameters of the replacement circuit.

Table 3.3, 3.4 shows the initial (catalog) data and the calculated parameters of the replacement circuits for a number of electric motors, obtained using this algorithm.

A comparison of the obtained SM parameters with the experimental data and the starting characteristics showed the high accuracy of the proposed algorithm.

Table 3.3 - Catalog data

Type ogf motor	P_N, kW	U_N, v	$\cos\varphi_N$	η_N, %	Tarting characteristics				Data on the field winding	
					$\frac{I_п}{I_н}$	$\frac{M_п}{M_н}$	$\frac{M_B}{M_н}$	$\frac{M_M}{M_н}$	$U_{fн}$, B	$I_{fн}$, A
CTD-1250-2	1250	10	0,9	96,5	6,48	2,07	1,5	1,67	45	255
CTD-1600-2	1600	10	0,9	96,9	6,79	2,16	1,6	1,66	52	273
CTD-2000-2	2000	10	0,9	96,8	6,91	2,23	1,63	1,61	59	290
CTD-2500-2	2500	10	0,9	97,2	6,16	1,75	1,5	1,71	76	260
CTD-3200-2	3200	10	0,9	97,3	6,48	2,07	1,5	1,67	45	255
CTD-4000-2	4000	10	0,9	97,4	6,69	1,92	1,66	1,72	103	294

Table 3.4-Calculation parameters of the substitution scheme

Тип	$R_{ст}$	R_f	R_{1c}	R_{1p}	X_σ	X_{ad}	$X_{\sigma f}$	$X_{\sigma 1c}$	$X_{\sigma 1p}$
CTD-1250-2	0,0126	0,00229	0,0289	0,0588	0,108	2,11	0,109	0,0657	0,0323
CTD-1600-2	0,0112	0,00224	0,0268	0,056	0,103	2,13	0,104	0,0644	0,0308
CTD-2000-2	0,0115	0,00233	0,0284	0,0558	0,101	2,41	0,102	0,0605	0,0307
CTD-2500-2	0,0101	0,00182	0,0207	0,0533	0,121	1,88	0,117	0,0756	0,0293
CTD-3200-2	0,00972	0,00167	0,018	0,0484	0,114	1,77	0,108	0,0716	0,0266
CTD-4000-2	0,00936	0,00173	0,0185	0,0498	0,111	1,84	0,107	0,0738	0,0274

3.3 Determination of the loss of active power in synchronous motors with polished poles

The energy conversion in a synchronous machine is associated with energy losses. All types of losses in the synchronous machine are divided into basic and additional.

The main losses in a synchronous machine are composed of electrical losses in the stator winding, loss of excitation, magnetic losses and mechanical losses.

Electrical losses in the stator winding [33]:

$$\Delta P_1=I^2\times R_s \qquad (3.54)$$

where R_s— active resistance of one phase of the stator winding at the design operating temperature, Om.

Loss of excitement

$$\Delta P_f=I^2\times X_{ad}\times R_f \qquad (3.55)$$

Magnetic losses of the synchronous machine occur in the stator core, which is subject to magnetization reversal by a rotating magnetic field. These losses consist of losses from hysteresis due to eddy currents

$$\Delta P_{12} \cong \frac{U^2}{R_m(U)}, \tag{3.56}$$

Mechanical losses (W), equal to the sum of friction losses in bearings and losses for ventilation.

The ratio of these types of power losses, which are ultimately determined by the load factors of electric motors, essentially determines the type of static power loss characteristics.

For research, the static characteristics of power losses are considered for the example of synchronous motors with a heavy-duty and massive rotor.

Figure 3.2 shows the static characteristics of the total losses of active power in a high-voltage synchronous motor with a shunt rotor VDN-18-74-16 (P_{nom} = 4000 kW) with load factors (K_3) from 0.5 to 1. The following designations are used: $\Delta P_{\Sigma СД}$(Kl=1) are the total losses of active power with a load factor of 1; $\Delta P_{\Sigma СД}$(Kl=0,9) – the total losses of active power with a load factor of 0.9, etc .;

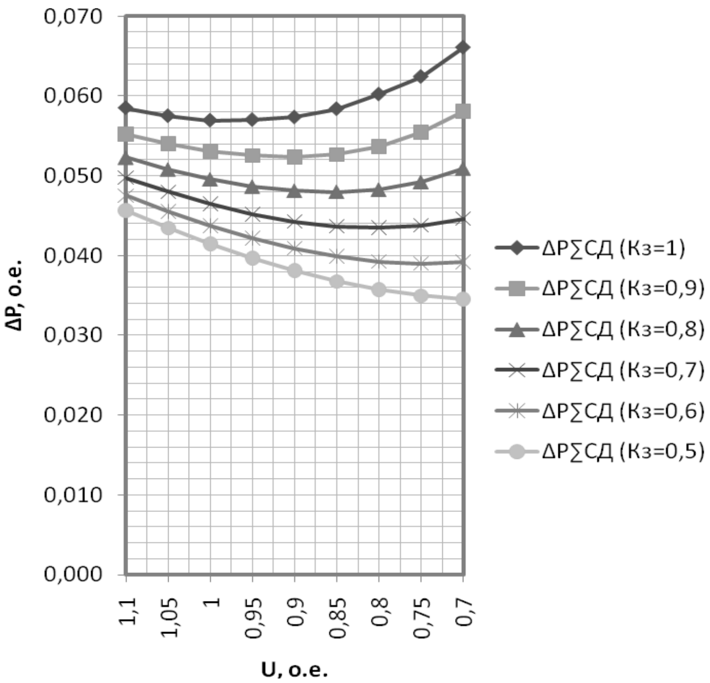


Figure 3.2 - Static characteristics of active power loss in VDN-18-74-16 for various load factors

Figure 3.3 shows the static characteristics of the total losses of active power in a high-voltage synchronous motor with a shield rotor VDN-18-44-32 (P_{nom} = 1250 kW) with load factors (K_3) from 0.5 to 1.

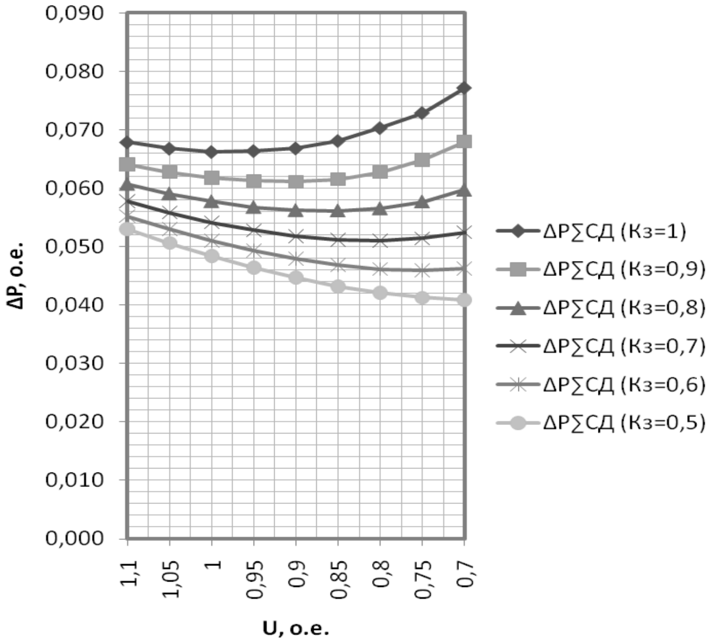


Figure 3.3 - Static characteristics of active power losses in VDN-18-44-32 for various load factors

Figure 3.4 shows the static characteristics of the total losses of active power in a high-voltage synchronous motor with a massive rotor STD-1600-2 (P_{nom} = 1600 kW) with load factors (K_3) from 0.5 to 1.

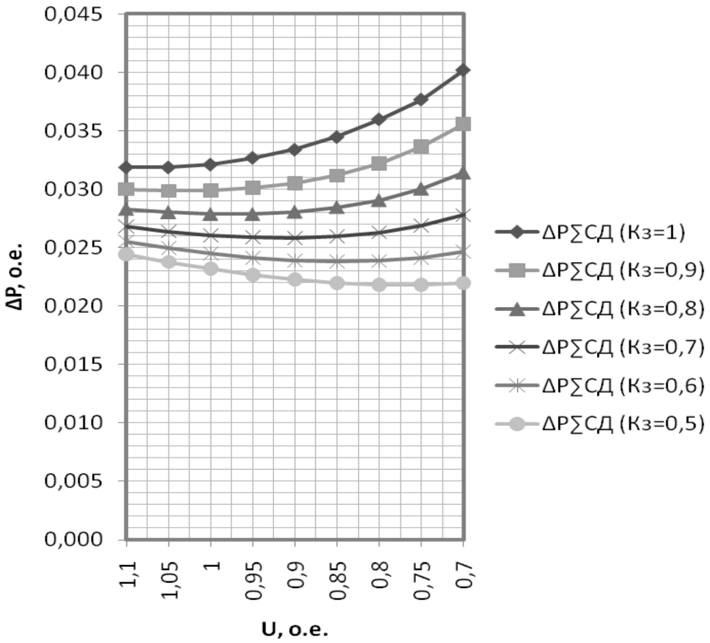


Figure 3.4 - Static characteristics of active power losses in STD-1600-2 for various load factors

Figure 3.5 shows the static characteristics of the total losses of active power in a high-voltage synchronous motor with a massive rotor STD-10000-2 (P_{nom} = 10,000 kW) with load factors (K_3) from 0.5 to 1.

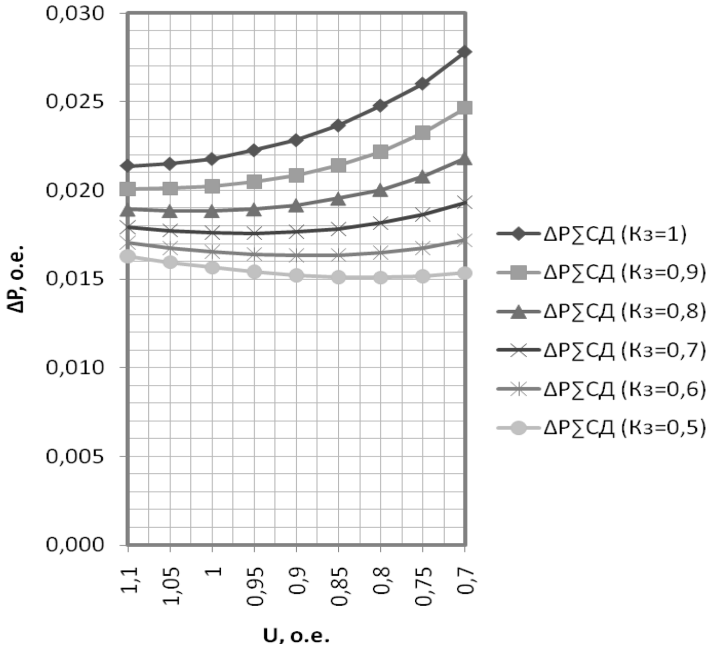


Figure 3.5 - Static characteristics of active power losses in STD-10000-2 for different load factors

Figure 3.6 shows the static characteristics of the total losses of active power in a low-voltage synchronous motor with a shipped SD2-74 / 25-604 rotor (P_{nom} = 225 kW) with load factors (K_3) from 0.5 to 1.

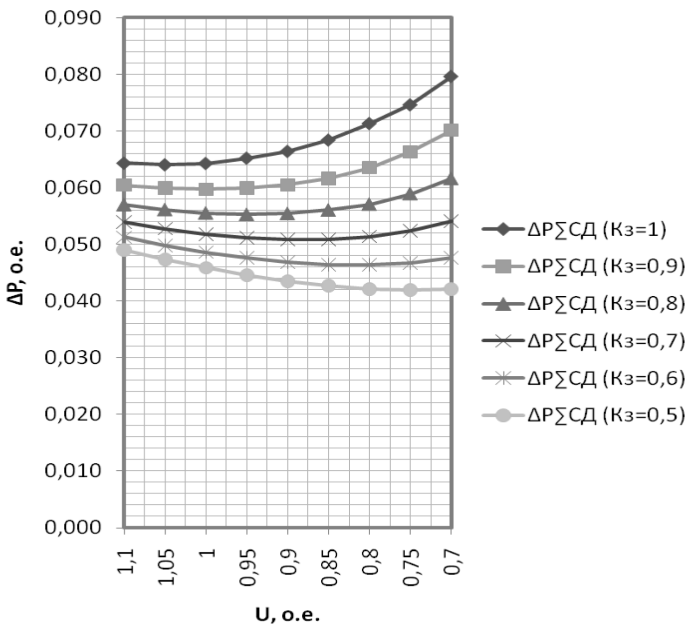


Figure 3.6 - Static characteristics of active power losses in SD2-74 / 25-604 at different load factors

At the nominal voltage at the terminals, the synchronous motor, operating at full load, consumes active power from the network. In case of changing the mains voltage, the active power on the motor shaft remains practically constant, only the losses of active power in the engine change.

Analysis of the dependence of the change in the value of active losses for various types of motors on the voltage at their terminals shows that the most significant effect is the value of the load factor of the engine.

3.4 Conclusion on the chapter

1. The methodology, algorithm and program for calculating the parameters of the substitution circuit and starting characteristics, SMs with shield poles with respect to the determination of the static characteristics of power losses are developed.

2. The methodology, algorithm and program for calculating the parameters of the replacement circuit and starting characteristics, SM with a massive smooth rotor as applied to the determination of the static characteristics of power losses are developed.

3. The voltage at the terminals, at which the minimum of the total losses of the active power of the SM with the bonded poles is guaranteed, essentially depend on the load factor and vary with a change in the load factor from 1 to 0.5 in the range from 1.1 to 0.7 of the nominal.

4. The voltage at the terminals, at which the minimum of the total active power loss of the SM with a massive smooth rotor is ensured, substantially depend on the load factor and vary with a change in the load factor from 1 to 0.5 in the range from 1.1 to 0.7 of the nominal.

4 STUDY OF STATIC CHARACTERISTICS OF LOAD CAPACITY AND LOSS OF POWER

4.1 Static power and power losses of the workshop substations of SSGP JSC for various load factors.

JSC "Sokolovsko-Sarbaiskoye Ore Mining and Processing Enterprise" (JSC "SSGP") is the largest enterprise in Kazakhstan and the countries of the Commonwealth of Independent States for the preparation of iron ore. The main products are fluxed iron ore pellets and iron ore concentrate. This high-quality raw material for blast-furnace production, corresponding to world standards, is in high demand among metallurgists.

The source of crude iron ore for processing at the concentration plants of the associations are Sarbai, Sokolovskiy, Kacharskiy, Kurzhunkulskiy quarry and Sokolovsky underground mine. Open mines - unique engineering structures, the depth of Sarbaiskiy reached -427 meters (projected 610 meters), Sokolovskiy -480 meters (design 580 meters), Kacharsky-297 meters (design 750 meters). The total balance reserves of the fields are 3411 million tons.

The design capacity of the crushing and processing plant is 31 million tons per year. It consists of large and medium-fine crushing shells, dry magnetic separation.

Iron ore fluxed pellets are a commodity product of JSC " SSGP" and are intended for smelting pig iron in blast furnaces.

In the technology of pellet production, the main building is used, including a limestone and clay (bentonite) grinding department, a pelletizing unit, a firing unit; Sorting cases Nos. 1 and 2; crushed limestone body; slurry pumping station; warehouse of finished pellets; Covered and open warehouPSS for components of charge; loading bunkers of pellets №1, 2, 3.Technological equipment is shown in Table 4.1.

Figure 4.2 presents the scheme of the technological process of the ore-preparation complex of JSC SSGPO

The power supply to the central office is carried out from 2 transformer substations No. 26 6 / 0,4 kV through transformers of 1000 kVA each. In turn, PS No. 26 feeds on mutually redundant current conductors laid above the ground from the upstream 2 transformer substation No. 34. The substation No.34 has two transformers (40 MVA) of 110/6 and 35/6 kV transformers, the power supply of Substation # 34 is supplied from the Sarbaiskaya-Aglomerat VL No. 1 voltage 110 kV from the Sarbaiskaya substation to KEGOC and 35 kV overhead lines from CHP.

The total number of elements of PSS - 352, including cables (117 connections with a total length of about 9000 m, spread of connection lengths - from 10 to 180 m, spread of cable connection cross-sections from 2 × (3 × 240) to 3 × 4 mm2, and also 91 AM and 12 SM with the total installed capacity of 17915 kW, the average power of the engines is 173.93 kW (twenty have a power of over 100 kW: 2 to 2000, 10 to 800, 4 to 500, 4 to 400 kW, a minimum power of 0.5 kW).

Other (non-motor) load of 0.38 kV is represented by lighting, signaling and thyristor airborne devices (TSS) SM

Table 4.1 - Process equipment pellets, baking and sorting

Equipment	Quantity
1. Overloader with a bridge load-carrying capacity of 15 tons	2
2. Crusher DMPE1450*1300 (200 t / h)	2
3. Ball mill Ш-25A with the size of 5700*3200 mm (25 t / h)	8
4. Two-shaft screw-type mixer measuring 4800*600 mm	36
5. Continuous belt dispenser	72
6. Pellet rebate, 11 m long, 2.8 m in diameter	36
7. The screen of GIT-51, equipped with a steel mesh of 10*70 mm	36
8. Conveyor machine type OK-108	4
9. Conveyor machine type OK-116	8
10. Roller stacker PR-5-2200	12
11. Screens 173Gr	6
12. The fluidized bed cooler OKS-85 (on the water meter No. 12)	1
13. Drum cooler (on the water meter №№ 9-11)	3
14. Aspiration and technical installations	94
15. Air separators of SPVV type with a diameter of 4250 mm	8

Figure 4.1 shows the static characteristics of the total losses of active power in the scheme under consideration with the load factor (K3) - 0.9 AM and SM. The following designations are accepted: $\Delta P_{\Sigma СД}$ - total losses of active power in SM (including losses in the chain of connection of motors); $\Delta P_{\Sigma АД}$ - total losses of active power in AD (including losses in the chain of connection of motors); $\Delta P_{сети}$ - active power losses in the electric network, with the exception of losses in the connections of AM and SM; $\Delta P_{\Sigma трансф}$ is the total active loss of steel in transformers; ΔP_{Σ} - total active power losses in PSS, including active power losses in the network, AM and SM.

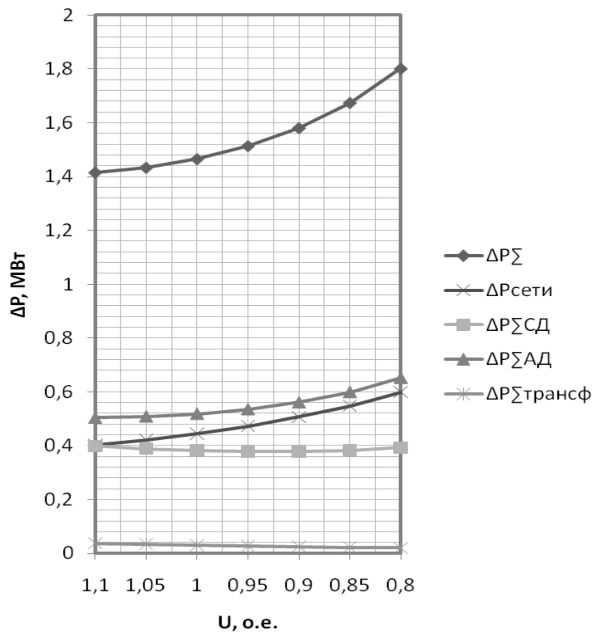


Figure 4.1 - Static Characteristics of Active Power Loss for TP-26

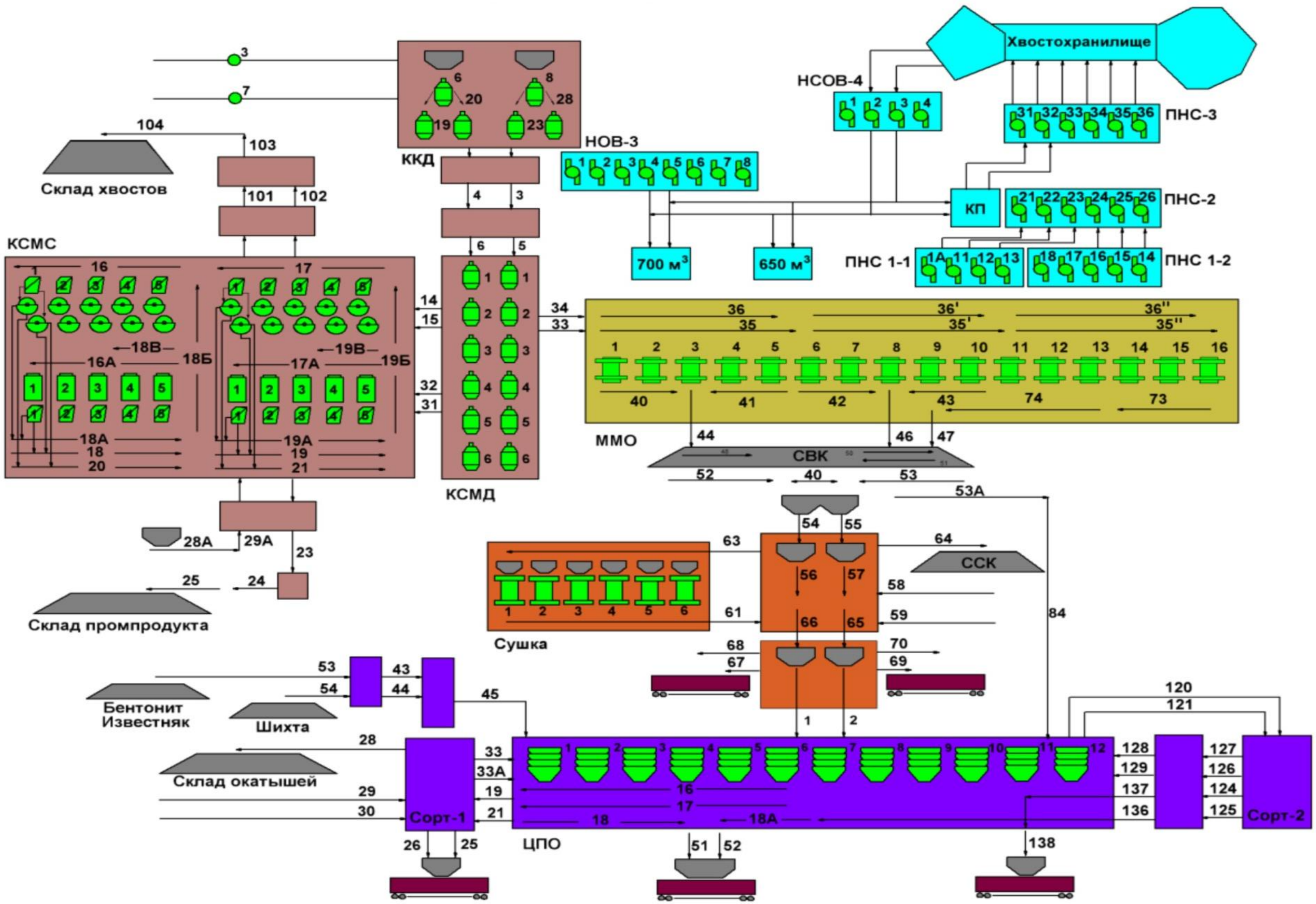


Figure 4.2 - The scheme of the technological process of the ore-preparation complex of JSC SSGPO

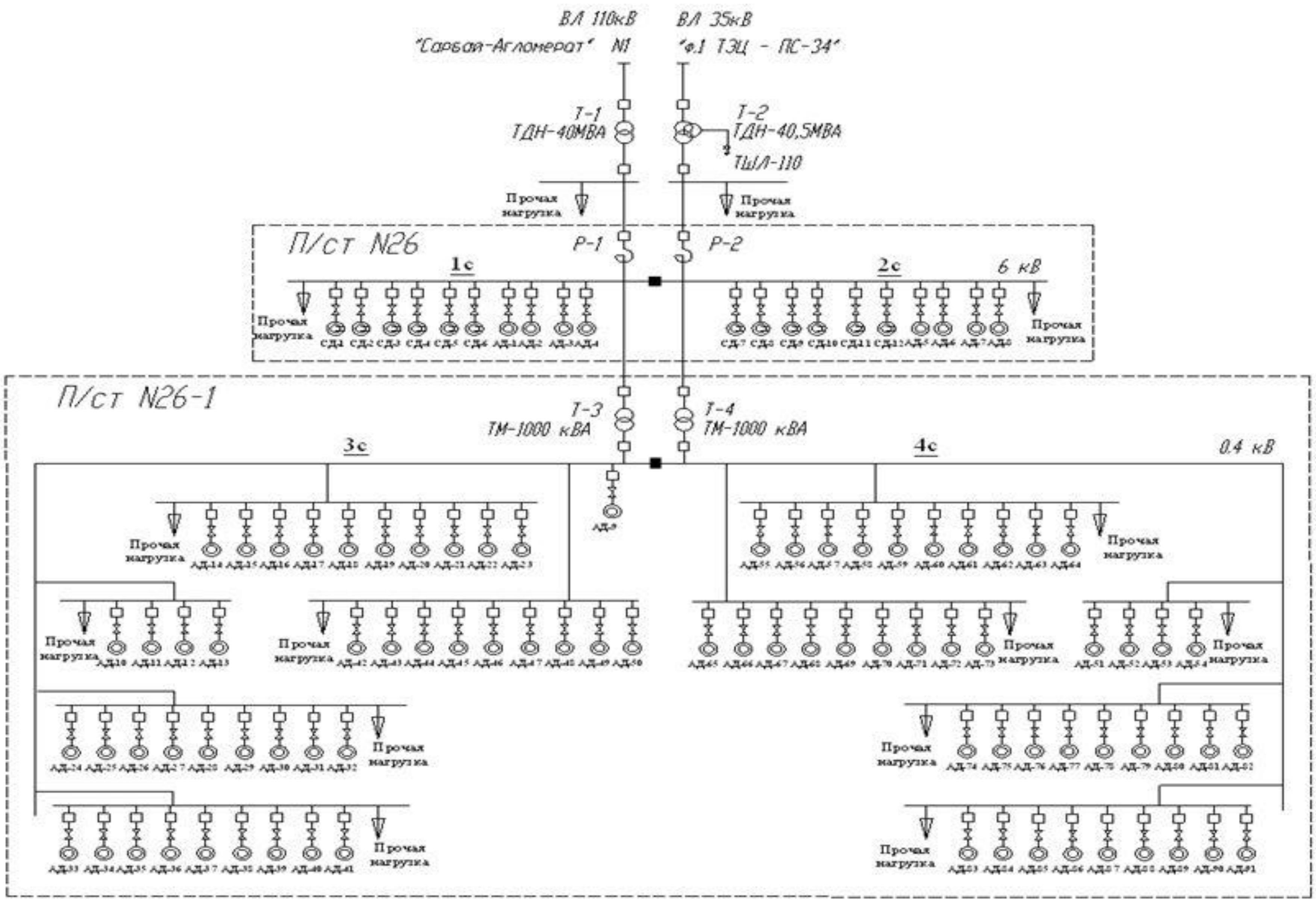


Figure 4.2 - Settlement scheme TP-26 of JSC SSGPO

Figure 4.3 shows the static characteristics of the total losses of active power in the scheme under consideration with the load factor (K3) - 0.9 AM and SM. The following designations are accepted: $\Delta P_{\Sigma СД}$ - total losses of active power in SM (including losses in the chain of connection of motors); $\Delta P_{\Sigma АД}$ - total losses of active power in AD (including losses in the chain of connection of motors); $\Delta P_{сети}$ - active power losses in the electric network, with the exception of losses in the connections of AM and SM; $\Delta P_{\Sigma трансф}$ is the total active loss of steel in transformers; ΔP_{Σ} - total active power losses in PSS, including active power losses in the network, AM and SM.

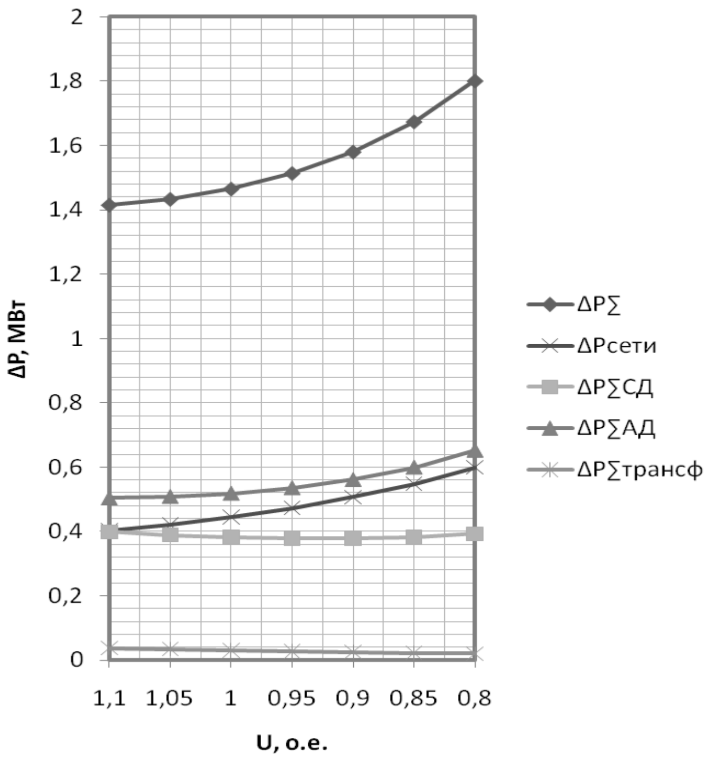


Figure 4.3 - Static Characteristics of Active Power Loss for TP-26

Figure 4.4 presents the static characteristics of the total losses of the active power of the AD in the circuit under consideration with K_3 = 0.9. The following designations are accepted: $\Delta P_{\Sigma АД}$ - total active power loss (includes losses in the engine connection circuit); АД; $\Delta P_{1АД}$ - total losses of active power in the steel of magnetic systems AM; $\Delta P_{2АД}$ - total losses of active power in stator windings; $\Delta P_{2АД}$ - total losses of active power in rotor windings; $\Delta P_{\Sigma АДкаб}$ - total losses of active power in the connections of AM.

Figure 4.5 presents the static characteristics of the total losses of the active power of the LED in the scheme under consideration with K_3 = 0.9. The following designations are accepted: $\Delta P_{\Sigma СД}$ - total losses of active power of SMs (including losses in the connection circuit of motors); $\Delta P_{12СД}$ - total losses of active power in the steel of magnetic SM systems; $\Delta P_{1СД}$ - total losses of active power in stator windings; $\Delta P_{fАД}$ - total losses of active power in the excitation winding SM; $\Delta P_{\Sigma СДкаб}$ - the total loss of active power in the connections to the SM.

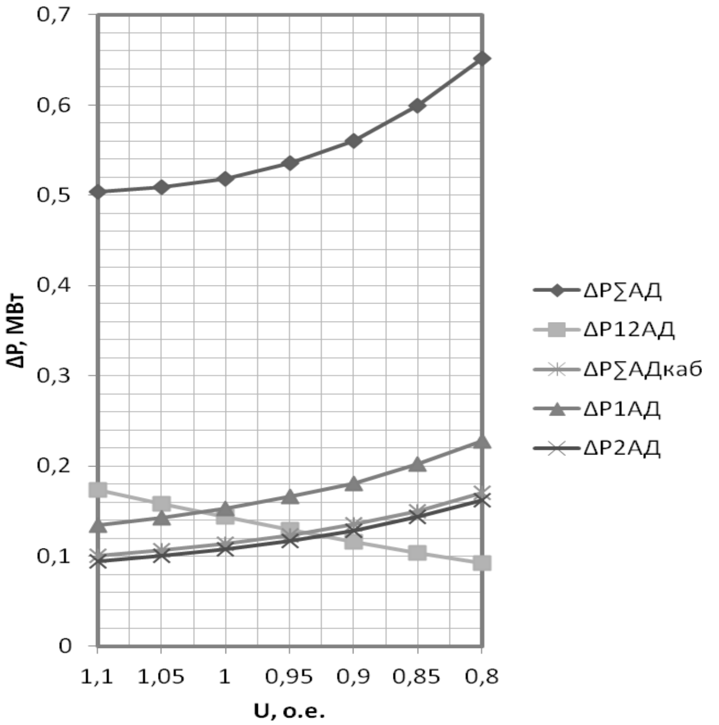


Figure 4.4 - Static loss characteristics active power in AM (K3 = 0.9)

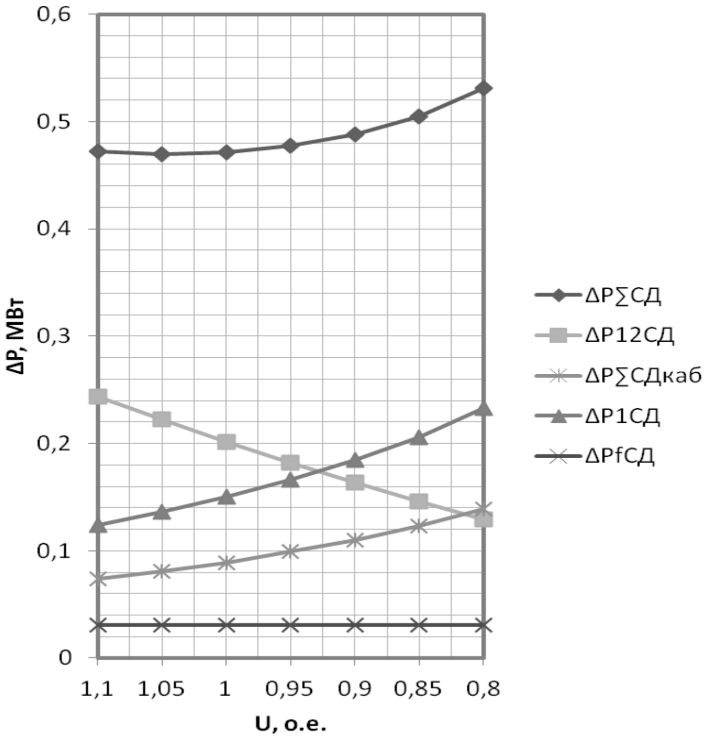


Figure 4.5 - Static characteristics of active power loss in SM (K_3 = 0.9)

Figure 4.6 presents the static characteristics of the consumption of reactive power in the scheme under consideration with K_3 = 0.9 AM and SM. The following designations have been adopted: $\Delta Q_{\Sigma АД}$ - consumption of reactive power in AD (including losses in the motor connection circuit); $\Delta Q_{12АД}$ Network - the consumption of reactive power in the electrical network, with the exception of losses in the connections of AM and SD; $\Delta Q_{12АД\ transf}$ - consumption of reactive power of steel in transformers; ΔQ_{12}- consumption of reactive power in PSS, including power losses in the network, AM and SM.

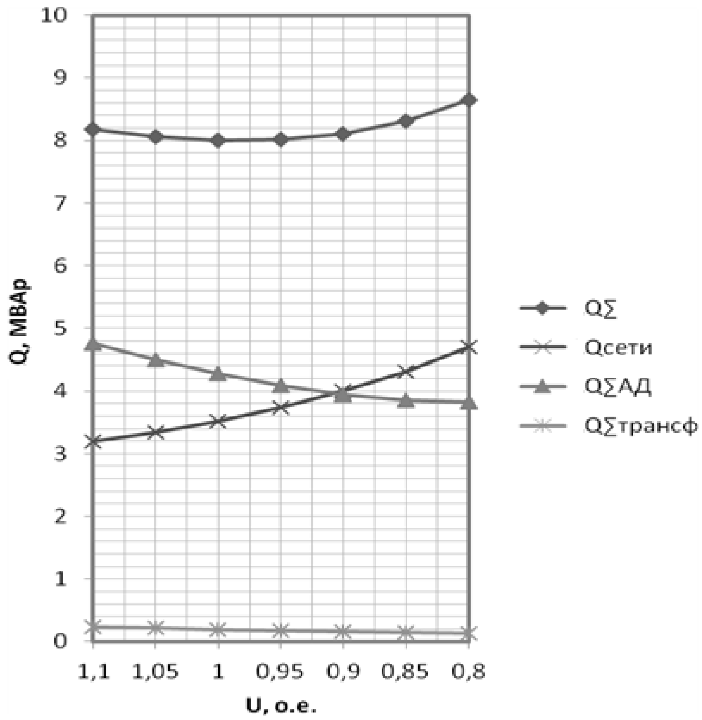


Figure 4.6 - Static consumption characteristics reactive power for TP-26

Figure 4.7 shows the static characteristics of the reactive power consumption of the AD in the circuit under consideration with K_3 = 0.9. The following designations have been adopted: $\Delta Q_{\Sigma АД}$ - reactive power consumption of the AD (including losses in the motor connection circuit); $\Delta Q_{12АД}$ - consumption of reactive power in the steel of magnetic systems of AM; $\Delta Q_{1АД}$ - consumption of reactive power in stator windings; АД; $\Delta Q_{2АД}$ - consumption of reactive power in the rotor windings of AM; $\Delta Q_{\Sigma АДкаб}$ the consumption of reactive power in AM connections.

Based on the analysis of the static characteristics of power losses in the workshop PSS at K_3 = 0.9 AM and SM, we state the following conclusions:

- Minimum losses of active power take place at K_3 = 0.9 AD and SD for the voltage at the terminals of transformers T1, T2 TP-26, equal to the voltage of the network (U = 1,1); they are equal to ΔP_{Σ} = 1,415 MW, which is 6.8% of the active power entering the transformers T1, T2 (P_{Σ} = 20,79MW)
- Total active power losses ΔP_{Σ} = 1,415 MW are made up of power losses in the workshop network ΔP_c = 402, kW, power losses in the PSS ADP $\Delta P_{\Sigma АД}$ = 503.48 kW, power losses in the PSS СЭР□СД = 472.36 kW, losses in steel transformers □Rtransf = 37.4 kW. Thus, the overwhelming share of the total losses of active power (almost 70%) is the electric power losses in the AD and SD of the PSS.

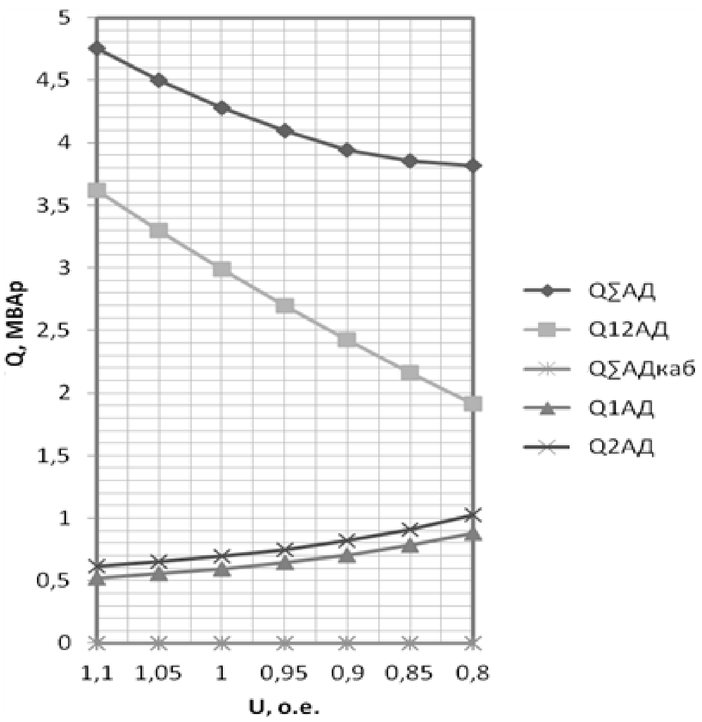


Figure 4.7 - Static consumption characteristics
reactive power in AM

- Electric losses of active power in the ADS PSS $\Delta P_{\Sigma СД}$ = 503.48 kW are composed of losses in the stator ($\Delta P_{1АД}$ = 134.33 kW, 26.7%) and rotary ($\Delta P_{2АД}$ = 94.42 kW, 18.7 %) windings, power losses in the steel of magnetic systems AM ($\Delta P_{12АД}$ = 173.73 kW, 34.5%) and loss of AM connection ($\Delta P_{присоед}$ = 101 kW, 20.1%). The total share of electrical and mechanical power losses in AM is 9.98% in the consumption of active power motors ($P_{\Sigma АД}$ = 5045.76 kW), which corresponds to the average efficiency of the electric load $\eta_{ср}$ = 90.02%. High efficiency is due to the fact that most of the active power consumes AM with a nominal power of more than 100 kW.
- Electric losses of active power in SMs PSS $\Delta P_{\Sigma СД}$ = 472.36 kW are composed of losses in the stator winding ($\Delta P_{1СД}$ = 123.93 kW, 26.2%) and in the excitation winding (ΔP_f = 30.57 kW, 6.5%), power losses in the steel of magnetic systems AM ($\Delta P_{12СД}$ = 243.86 kW, 51.6%) and the loss of connection SM ($\Delta P_{присоед}$ = 74 kW, 15.7%). The total share of electric and mechanical power losses in SD is 4.4% in the consumption of active power motors ($P_{\Sigma АД}$ = 10800 kW), which corresponds to the average efficiency of the electric load $\eta_{ср}$ = 95.6%. The high efficiency is due to the fact that active power consumes SM with a rated output of more than 100 kW.
- The minimum consumption of reactive power takes place at K_3 = 0.9 AM and the voltage at the terminals of transformers T1, T2 of TP-26 equal to the rated voltage of the network (U = 1) and they are equal to ΔQ_{Σ} = 8 MVAr
- Consumption of reactive power in AD PSS $\Delta Q_{\Sigma АД}$ = 4.76 MWar consists of losses in stator (ΔQ_{1AD} = 523.02 kVAr; 11%) and rotor windings ($\Delta Q_{2АД}$ = 612.74 kVAr;

12.88%), loss of power in the steel of the magnetic systems of AM ($\Delta Q_{12АД}$ = 3.62 mVar, 76.08%) and loss of adherence of AM ($\Delta P_{prisoed}$ = 2 kVar, 0.04%).

Figure 4.8 shows the static characteristics of the total losses of active power in the scheme under consideration with K3 = 0.8 AM and SM. The adopted designations are similar to Figure 4.3.

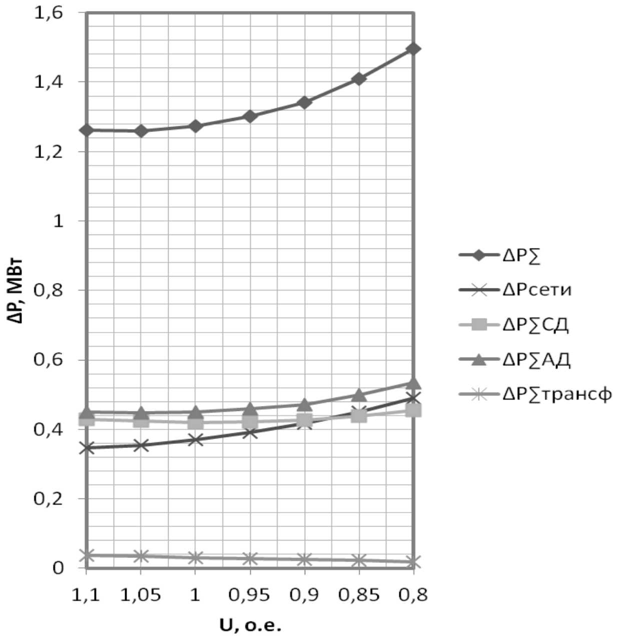


Figure 4.8 - Static loss characteristics active power for TP-26

Figure 4.9 shows the static characteristics of the total losses of the active power of the AM in the circuit under consideration with K_3 = 0.8. The adopted designations are similar to Figure 4.4.

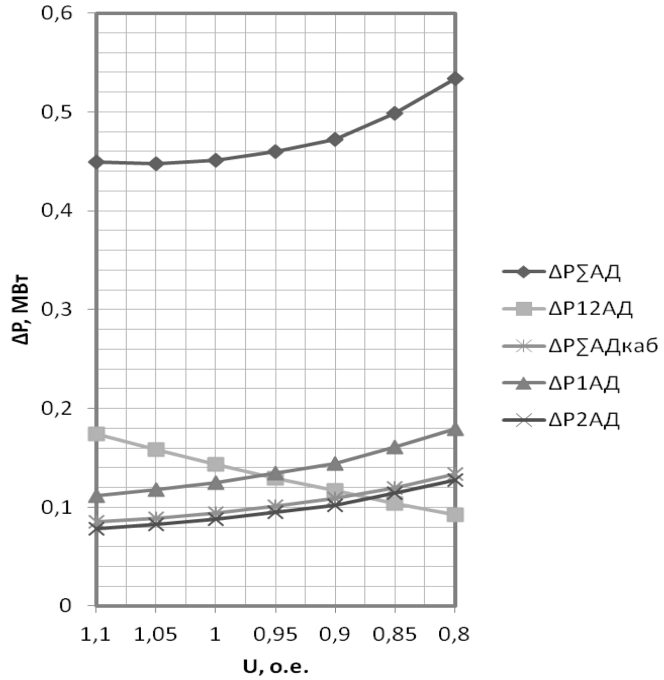


Figure 4.9 - Static loss characteristics of active power in AM (K_3 = 0.8)

Figure 4.10 shows the static characteristics of the total losses of the active power of the SM in the scheme under consideration with K_3 = 0.8. The accepted designations are similar to figure 4.5.

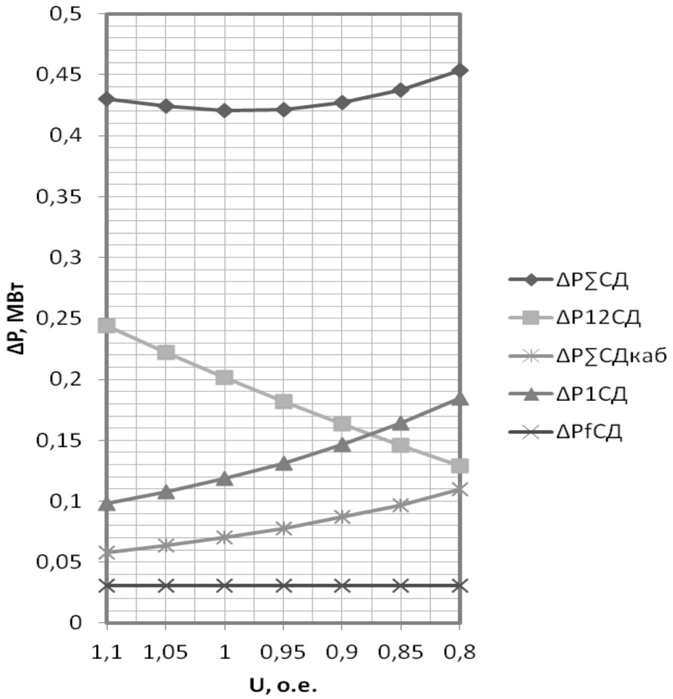


Figure 4.10 - Static characteristics of active power loss in SM (K_3 = 0.8)

Figure 4.11 shows the static characteristics of reactive power consumption in the circuit under consideration at K_3 = 0.8 AM and SM. The accepted designations are similar to Figure 4.6.

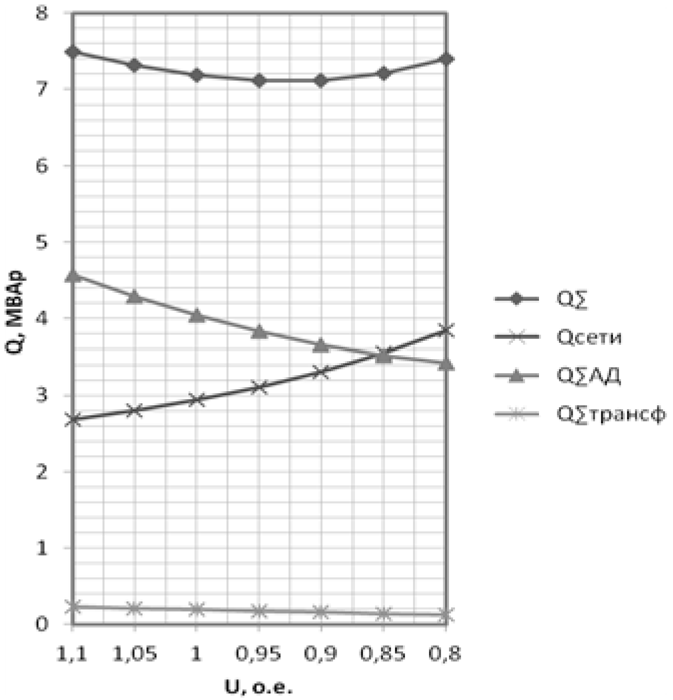


Figure 4.11 - Static consumption characteristics of reactive power for TP-26

Figure 4.12 shows the static characteristics of the consumption of reactive power of AM in the scheme under consideration with K_3 = 0.8. The adopted designations are similar to Figure 4.7.

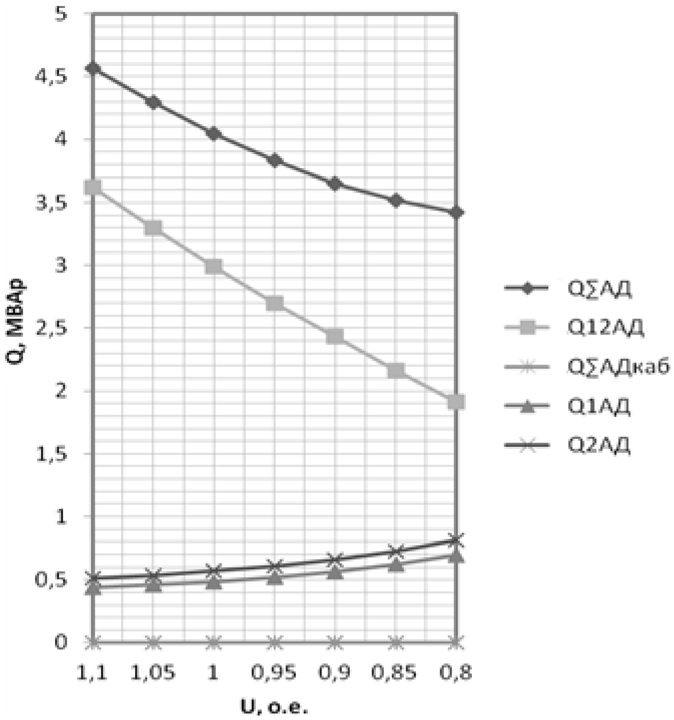


Figure 4.12 - Static consumption characteristics reactive power in AM (K_3 = 0.8)

Based on the analysis of the static characteristics of power losses in the workshop PSS at K_3 = 0.8 AM and SM, we formulate the following conclusions:

- Minimum losses of active power take place at K3 = 0.8 AM and SM at the voltage at the terminals of transformers T1, T2 TP-26, equal to the voltage of the network (U = 1.05); they are equal to ΔP_{Σ} = 1,259 MW, which is 6.8% of the active power entering the transformers T1, T2 (P_{Σ} = 18.58 MW).
- Total active power losses ΔP_{Σ} = 1,259 MW are made up of power losses in the workshop network ΔP_c = 353 kW, power losses in the HPS of the PSS $\Delta P_{\Sigma АД}$ = 447.79 kW, power losses in the PSS $\Delta P_{\Sigma СД}$ = 424 , 29 kW, losses in steel transformers $\Delta P_{\Sigma трансф}$ = 34.07 kW. Thus, the overwhelming share of the total losses of active power (about 69%) is the electric power losses in the AM and SM of the PSS.
- Electric losses of active power in AD PSS $\Delta P_{\Sigma АД}$ = 447.79 kW are composed of losses in stator ($\Delta P_{1АД}$ = 117,76 kW, 26,3%) and rotary ones ($\Delta P_{2АД}$ = 82,74 kW, 18,5 %) windings, power losses in the steel of the magnetic systems of AM ($\Delta P_{12АД}$ = 158.29 kW, 35.3%) and loss of adherence of AM ($\Delta P_{prisoed}$ = 89 kW, 19.9%). The total share of electrical and mechanical power losses in AM is 9.98% in the consumption of active power motors ($P_{\Sigma АД}$ = 4485.12 kW), which corresponds to the average efficiency of the electric load $\eta_{ср}$ = 90.02%. High efficiency is due to the fact that most of the active power consumes AM with a nominal power of more than 100 kW.

- Electric losses of active power in SDS SPS $\Delta P_{\Sigma СД}$ = 424.29 kW are composed of losses in the stator winding ($\Delta P_{1СД}$ = 107.53 kW, 25.3%) and in the excitation winding (ΔP_f = 30.57 kW; 7.2%), power losses in the steel of the magnetic systems of the AD ($\Delta P_{12СД}$ = 222.19 kW, 52.4%) and the loss of connection of the SD ($\Delta P_{присоед}$ = 64 kW, 15.1%). The total share of electrical and mechanical power losses in SM is 4.4% in the consumption of active power motors ($P_{\Sigma АД}$ = 9600 kW), which corresponds to the average efficiency of the electric load $\eta_{ср}$ = 95.6%. The high efficiency is due to the fact that active power consumes SM with a rated output of more than 100 kW.
- The minimum consumption of reactive power takes place at K_3 = 0.8 and the voltage at the terminals of transformers T1, T2 TP-26 equal to the mains voltage (U = 0.95) and they are equal to ΔQ_{Σ} = 7.114 MVAr.
- Consumption of reactive power in AM PSS $\Delta Q_{\Sigma АД}$ = 4.29 MWar consists of losses in stator (Q1AD = 458.73 kVAr, 10.68%) and rotor windings ($\Delta Q_{1АД}$ = 537.58 kVAr, 12.52%) windings , power losses in the steel of magnetic systems of AM ($\Delta Q_{12АД}$ = 3,3 mVar, 76,75%) and loss of adherence of AM ($\Delta P_{prisoid}$= 2 kVar, 0.05%).

Figure 4.13 shows the static characteristics of the total losses of active power in the scheme under consideration with K_3 = 0.7 AM and SM. The adopted designations are similar to Figure 4.3.

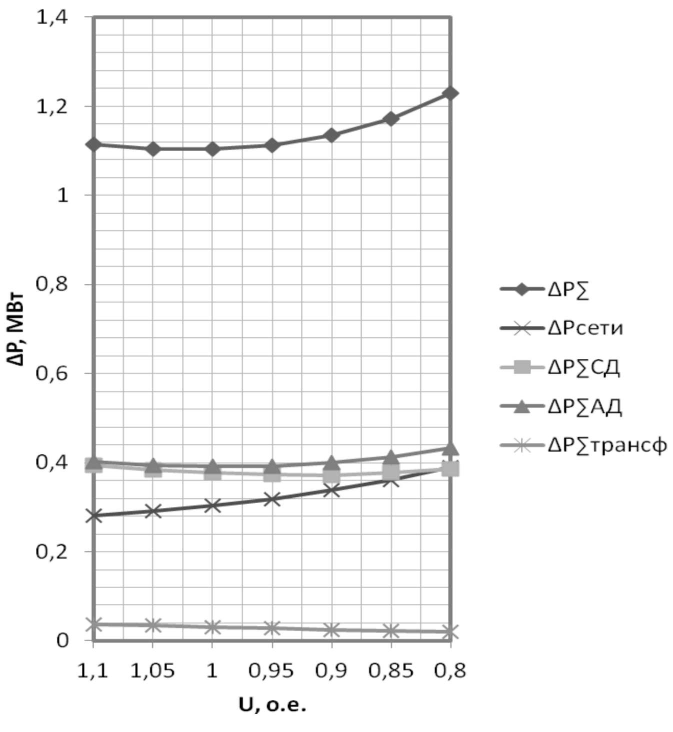


Figure 4.13 - Static loss characteristics active power for TP-26

Figure 4.14 shows the static characteristics of the total losses of the active power of the AM in the circuit under consideration with K_3 = 0.7. The adopted designations are similar to Figure 4.4.

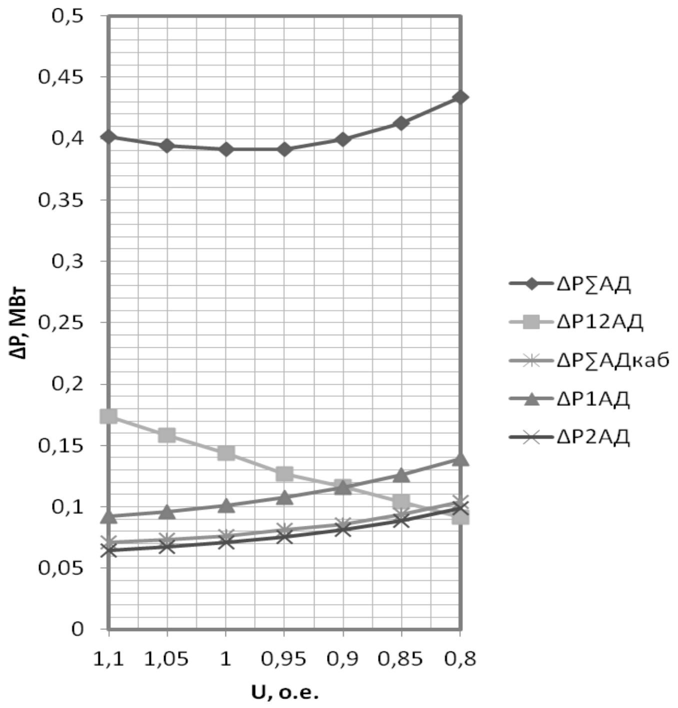


Figure 4.14 - Static loss characteristics active power in AM (K_3 = 0.7)

Figure 4.15 shows the static characteristics of the total losses of the active power of SMs in the scheme under consideration with K_3 = 0.7 AM and SM. The accepted designations are similar to figure 4.5.

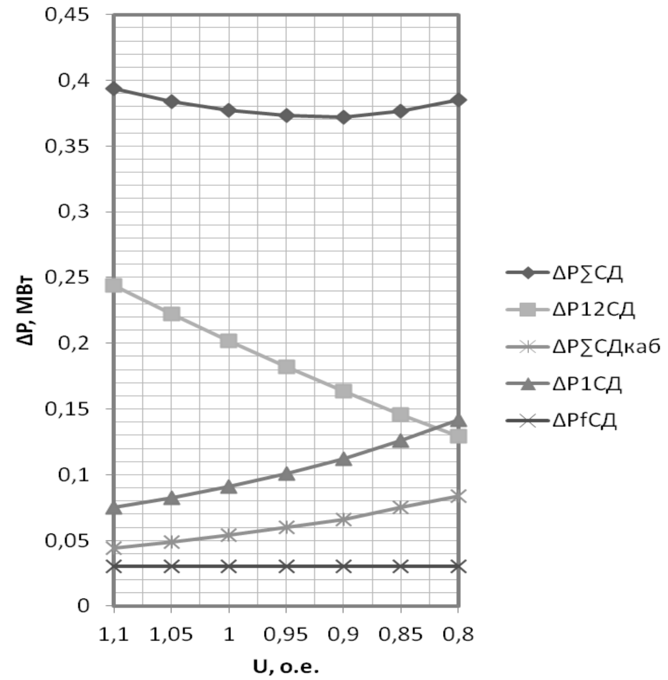


Figure 4.15 - Static characteristics of active power loss in SD (K_3 = 0.7)

Figure 4.16 shows the static characteristics of reactive power consumption in the scheme under consideration at K_3 = 0.7 AM and SM. The accepted designations are similar to Figure 4.6.

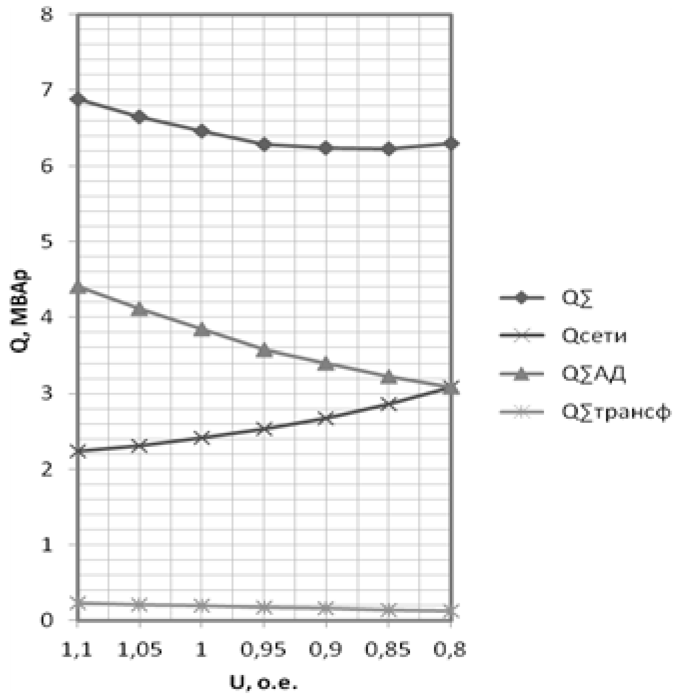


Figure 4.16 - Static characteristics of reactive power consumption for TP-26

Figure 4.17 shows the static characteristics of the consumption of reactive power of AM in the scheme under consideration with $K_3 = 0.7$. The adopted designations are similar to Figure 4.7.

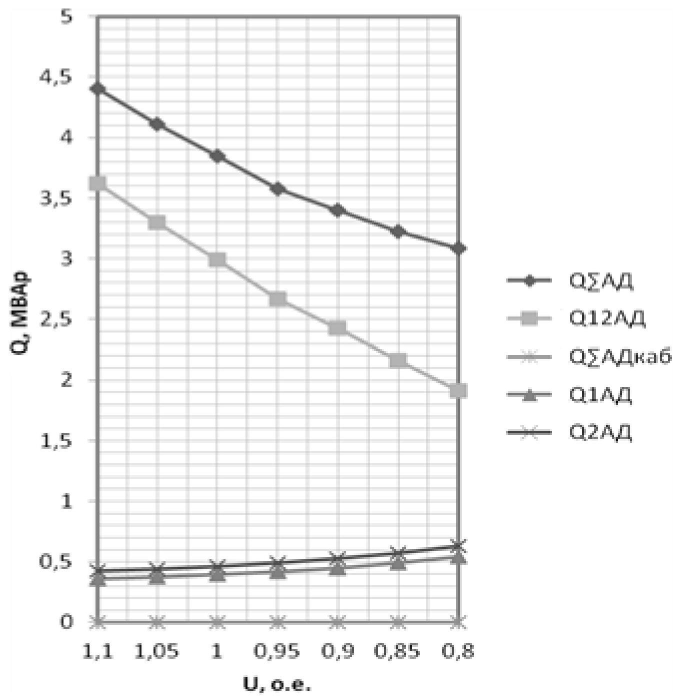


Figure 4.17 - Static consumption characteristics reactive power in AM ($K_3 = 0.7$)

Based on the analysis of the static characteristics of power losses in the shop PSS at $K_3 = 0.7$ AD and SD, we formulate the following conclusions:

- Minimum losses of active power take place at K_3 = 0,7 AM and SM at the voltage at the terminals of transformers T1, T2TP-26, equal to the voltage of the network (U = 1); they are equal to ΔP_Σ = 1,103 MW, which is 6.7% of the active power entering the transformers T1, T2 (P_Σ = 16.4W);

- Total active power losses ΔP_Σ = 1103,26kW are made up of power losses in the workshop network ΔP_c = 304 kW, power losses in the ADS SIS $\Delta P_{\Sigma АД}$ = 391.45 kW, power losses in the SDS SSR $\Delta P_{\Sigma СД}$ = 376.91 kW, losses in steel transformers $\Delta P_{\Sigma трансф}$ = 30.9 kW. Thus, the overwhelming fraction of the total active power losses (about 70%) is the electrical power losses in the AM and SM of the PSS;

- Electric losses of active power in the ADS PSS $\Delta P_{\Sigma АД}$ = 391.45 kW are composed of losses in the stator ($\Delta P_{1АД}$ = 100,96 kW, 25,8%) and rotary ($\Delta P_{2АД}$ = 70,92 kW, 18,1 %) windings, power losses in the steel of magnetic systems of AM (□P12AM = 143.57 kW, 36.7%) and loss of adherence of AM (□Proprieed = 76 kW, 19,4%). The total share of electrical and mechanical power losses in AM is 9.99% in the consumption of active power motors ($P_{\Sigma АД}$ = 3924.48 kW), which corresponds to an average efficiency of the electric load □pp = 90.01%. The high efficiency is due to the fact that most of the active power consumes AM with a nominal power of more than 100 kW;

- The minimum consumption of reactive power takes place at K_3 = 0.7A and SM voltage at the terminals of transformers T1, T2 TP-26, equal to the network voltage (U = 0.85) and they are equal to ΔQ_Σ = 6.221 MVAr;

- Consumption of reactive power in AD SPS $\Delta Q_{\Sigma АД}$ = 3.847 MBar consists of losses in the stator ($\Delta Q_{1АД}$ = 393.55 kVAr; 10.23%) and rotor windings ($\Delta Q_{2АД}$ = 489.01 kVAr; 12%), power losses in steel magnetic systems AM $\Delta Q_{12АД}$ = 2.99 mVar, 7.72%) and loss of adherence of AM ($\Delta P_{присоед}$ = 2 kVar, 0.05%).

Figure 4.18 shows the static characteristics of the total losses of active power in the scheme under consideration at K_3 = 0.6 AM and SM. The adopted designations are similar to Figure 4.3.

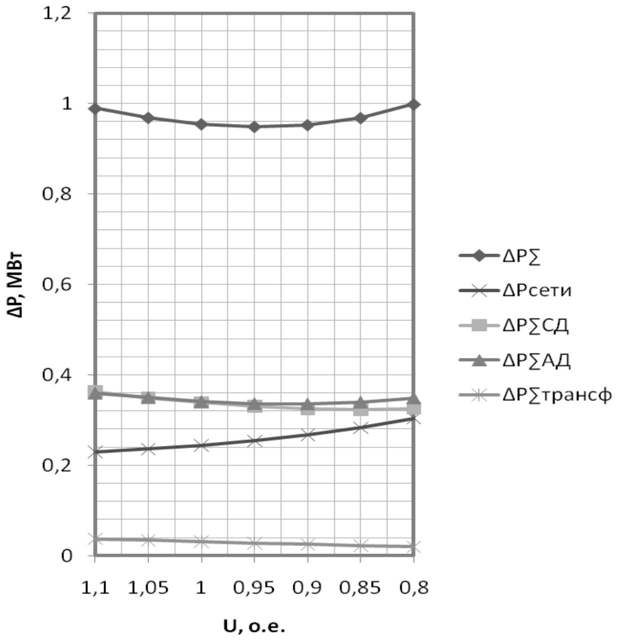


Figure 4.18 - Static Characteristics of Active Power Loss for TP-26

Figure 4.19 shows the static characteristics of the total losses of the active power of the AM in the scheme under consideration with K_3 = 0.6. The adopted designations are similar to Figure 4.4.

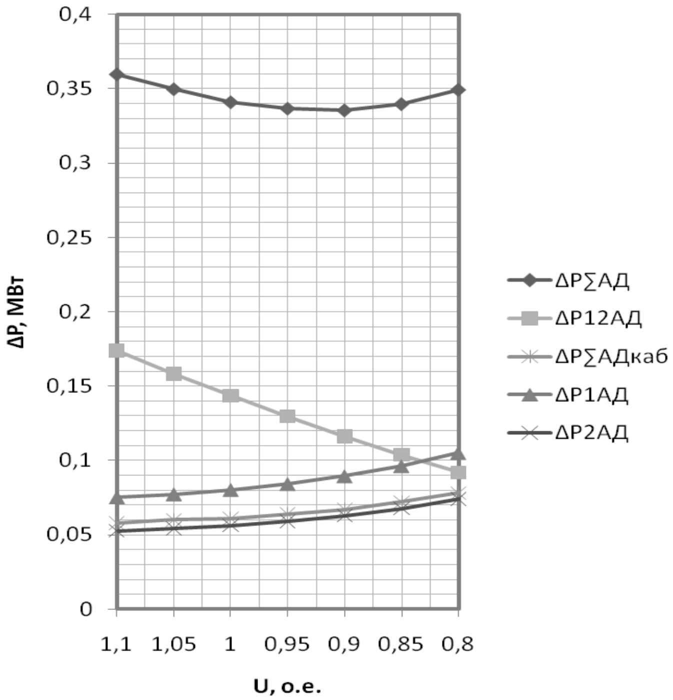


Figure 4.19 - Static characteristics of the loss of active power in AM (K_3 = 0.6)

Figure 4.20 shows the static characteristics of the total losses of the active power of the SM in the scheme under consideration with K_3 = 0.6. The accepted designations are similar to figure 4.5.

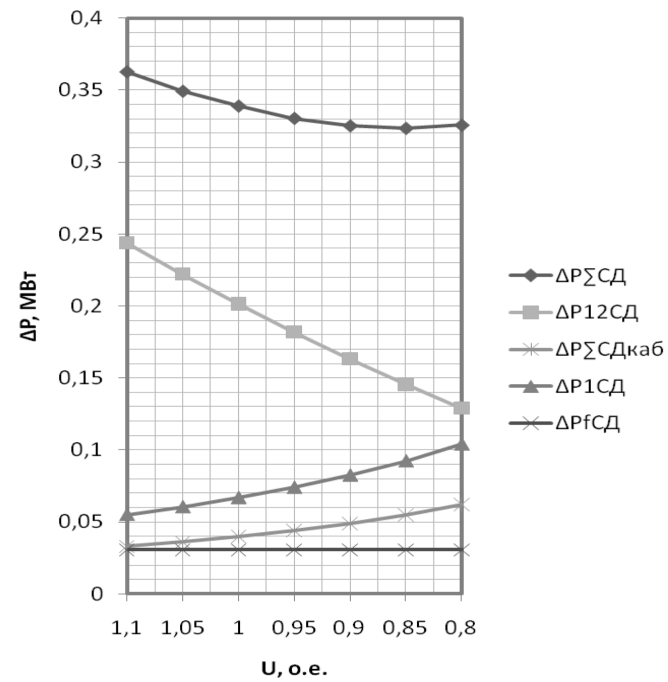


Figure 4.20 - Static characteristics of active power loss in SM (K_3 = 0.6)

Figure 4.21 shows the static characteristics of the consumption of reactive power in the scheme under consideration with K_3 = 0.6 AM and SM accepted designations are similar to Figure 4.6.

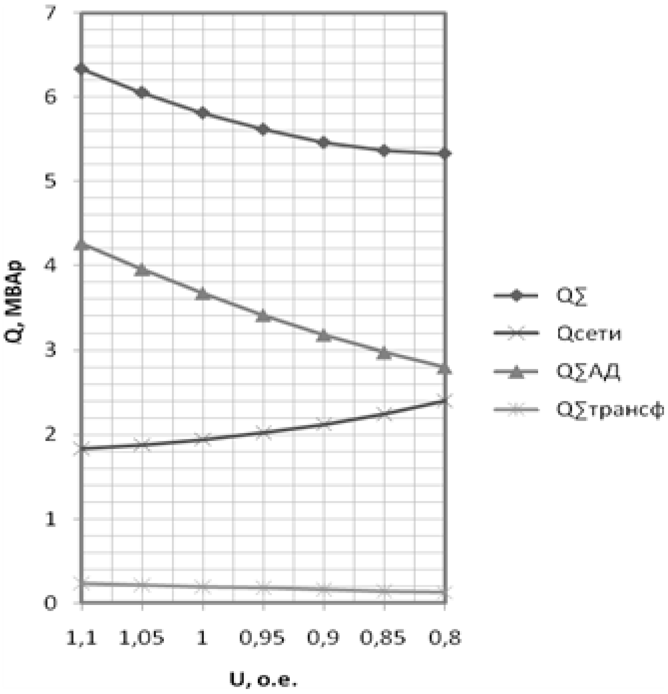


Figure 4.21 - Static Characteristics of Consumption of reactive power for TP-26

Figure 4.22 presents the static characteristics of the reactive power consumption of the AM in the circuit under consideration with K_3 = 0.6. The adopted designations are similar to Figure 4.7.

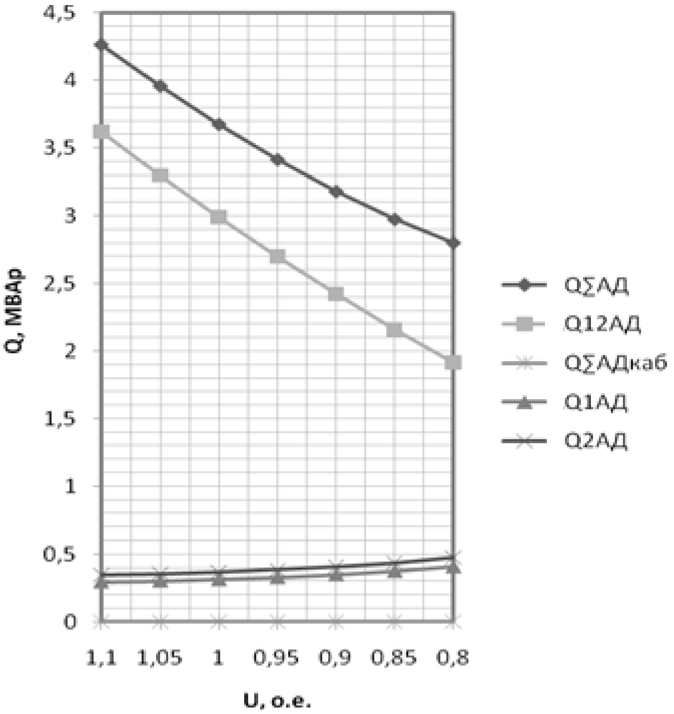


Figure 4.22 - Static Characteristics of Consumption of reactive power in AM (K_3 = 0.6)

Based on the analysis of the static characteristics of power losses in the workshop PSS at $K_3 = 0.6$ AM and SM, we formulate the following conclusions:

• Minimum losses of active power take place at $K_3 = 0.6$AM and SM at the voltage at the terminals of transformers T1, T2TP-26, equal to the mains voltage (U = 0.95); they are equal to $\Delta P_{\Sigma} = 949.02$ MW, which is 6.7% of the active power entering transformers T1, T2 ($P_{\Sigma} = 14.25$ MW)

- Total active power losses $\Delta P_{\Sigma} = 949{,}02$ kW are made up of power losses in the workshop network $\Delta P_c = 254$ kW, power losses in the ADS PSS $\Delta P_{\Sigma SM} = 336.75$ kW, power losses in the SM PSS $\Delta P_{\Sigma АД} = 330.39$ kW, losses in steel transformers $\Delta P_{\Sigma transform} = 27.88$ kW. Thus, the overwhelming share of the total active power losses (about 70%) is the electrical power losses in AM and SM of the PSS;

- Electric losses of active power in the AM PSS $\Delta P_{\Sigma АД} = 336.75$ kW are composed of losses in the stator ($\Delta P_{1АД} = 84{,}11$ kW, 25%) and rotary ($\Delta P_{2АД} = 59.06$ kW, 17.5%) windings, power losses in the steel of magnetic systems AM ($\Delta P_{12АД} = 129.58$ kW, 38.5%) and loss of connection with AM ($\Delta P_{connect} = 64$ kW, 19%). The total share of electrical and mechanical power losses in BP is 10% in the consumption of active power motors ($P_{\Sigma AM} = 3363{,}84$кВт), which corresponds to the average efficiency of the electric load $\eta_{av} = 90\%$. High efficiency is due to the fact that most of the active power consumes AM with a nominal power of more than 100 kW.

- Electric losses of active power in SM PSS $\Delta P_{\Sigma СД} = 330.39$ kW are composed of losses in the stator winding ($\Delta P_{1SM} = 73.93$ kW, 22.4%) and in the field winding ($\Delta P_f = 30.57$ kW; 9.3%), power losses in the steel of magnetic systems AM ($\Delta P_{12SM} = 181.89$ kW, 55%) and the loss of connection of SM ($\Delta P_{coonect} = 44$ kW, 13.3%). The total share of electrical and mechanical power losses in SM is 4.6% in the consumption of active power motors ($P_{\Sigma AM} = 7200$ kW), which corresponds to an average efficiency of the electric load $\eta_{av} = 95.4\%$. The high efficiency is due to the fact that active power consumes SM with a rated output of more than 100 kW.

- From the data obtained by calculation, it follows that the value of the reactive power consumption decreaPSS with decreasing voltage (from U = 1,1 to U = 0,8 of the rated voltage) at the terminals of the transformers T1, T2 TP-26 with the load factor of asynchronous and synchronous motors equal to 0.6 ;

- Consumption of reactive power in AM PSS $\Delta Q_{\Sigma AM} = 3{,}414$ MBar are composed of losses in stator ($\Delta Q_{1AM} = 328.12$ kVar, 9.61%) and rotor ($\Delta Q_{2AM} = 384.7$ kVAr, 11.28%) windings, losses power in the steel of magnetic systems of AM ($\Delta Q_{12AM} = 2.7$ mVar, 70.05%) and loss of adherence of AM ($\Delta P_{connect} = 2$ kVar, 0.06%).

Figure 4.23 shows the static characteristics of the total losses of active power in the scheme under consideration at $K_l = 0.5$ AM and SM. The adopted designations are similar to Figure 4.3.

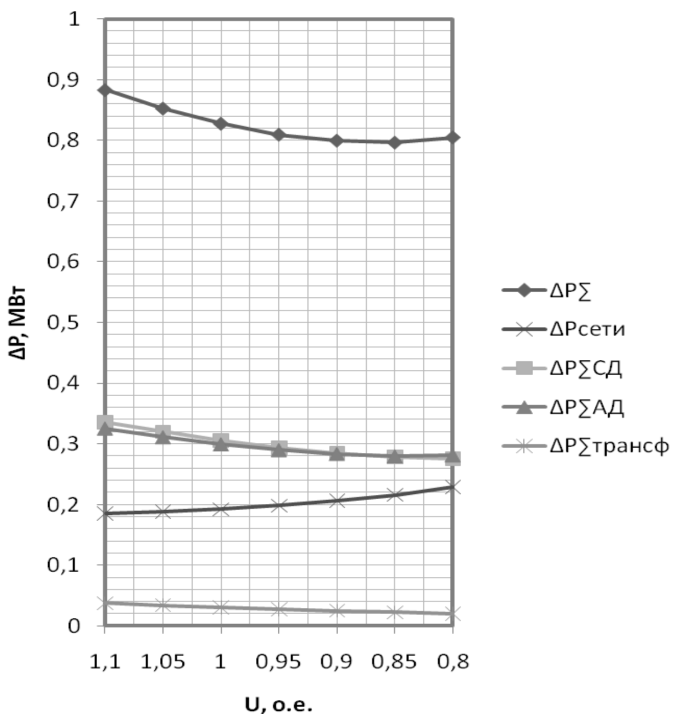


Figure 4.23 - Static loss characteristics of active power for TP-26

Figure 4.24 shows the static characteristics of the total losses of the active power of the AM in the scheme under consideration with K_l = 0.5. The adopted designations are similar to Figure 4.4.

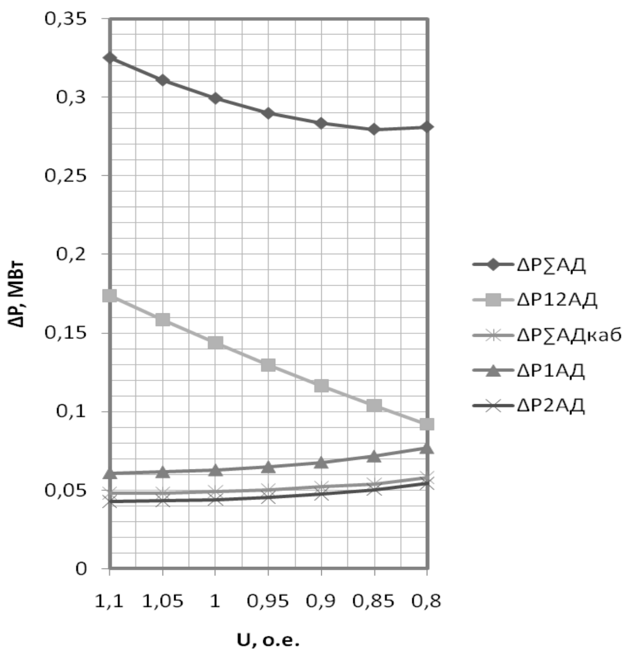


Figure 4.24 - Static characteristics of active power losses in AM (K_l = 0.5)

Figure 4.25 shows the static characteristics of the total losses of the active power of the SM in the scheme under consideration with K_l = 0.6. The accepted designations are similar to figure 4.5.

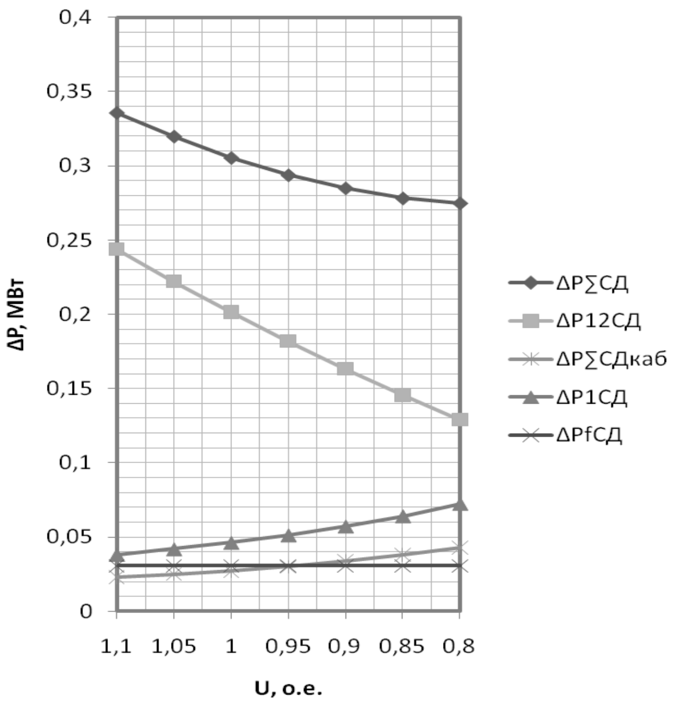


Figure 4.25 - Static loss characteristics active power in SM (K_l = 0.5)

Figure 4.26 shows the static characteristics of reactive power consumption in the scheme under consideration at K_l = 0.5 AM and SM. The accepted designations are similar to Figure 4.6.

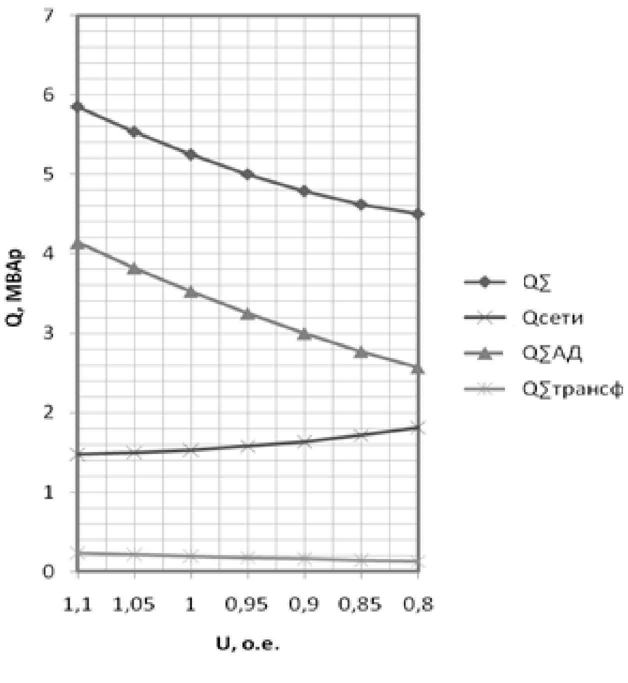


Figure 4.26 - Static consumption characteristics of reactive capacity for the TP-26 (K_l = 0.5)

Figure 4.27 shows the static characteristics of the reactive power consumption in the scheme under consideration with K_l = 0.5. The adopted designations are similar to Figure 4.7.

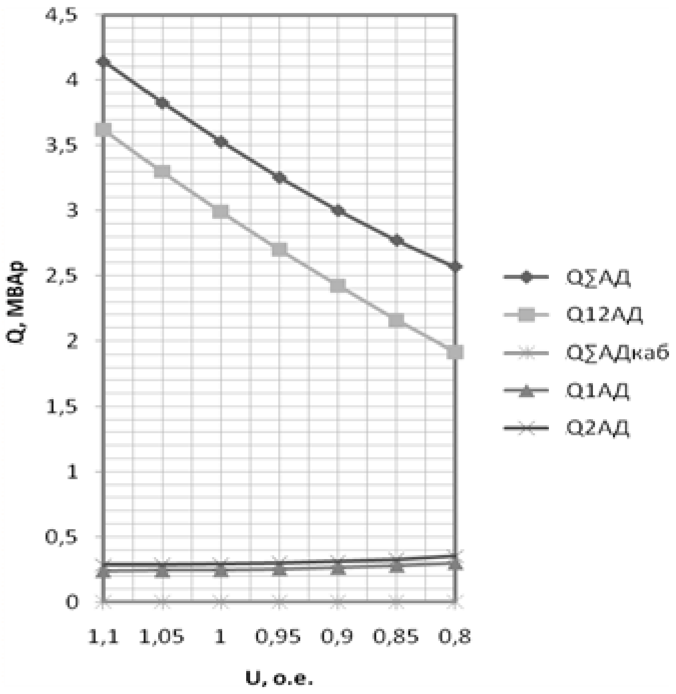


Figure 4.27 - Static characteristics of consumption of reactive power in AM (K_l = 0.5)

Based on the analysis of the static characteristics of the power losses in the shop PSS at K_3 = 0.5 AM and SM, we formulate the following conclusions:

- Minimum losses of active power take place at K_l = 0,5 AM and SM for the voltage at the terminals of transformers T1, T2TP-26, equal to the mains voltage (U = 0.85); they are equal to ΔP_{Σ} = 796.14MW, which is 6.8% of the active power entering transformers T1, T2 (P_{Σ} = 11.75 MW)
- Total losses of active power ΔP_{Σ} = 796.14 kW are made up of power losses in the workshop network ΔP_c = 216 kW, power losses in AM of the PSS $\Delta P_{\Sigma СД}$ = 279.58 kW, power losses in the PSS $\Delta P_{\Sigma СД}$ of SM = 278.24 kW, losses in steel transformers $\Delta P_{\Sigma трансф}$ = 22.32 kW. Thus, the overwhelming share of the total active power losses (about 70%) is the electrical power losses in AD and SD of the PSS.
- Electric losses of active power in AD PSS $\Delta P_{\Sigma АД}$ = 279.58 kW are composed of losses in stator (ΔP_{1AM} = 71.58 kW, 25.6%) and rotary (ΔP_{2AM} = 50.27 kW, 18%) windings, power losses in the steel of magnetic systems of AM (ΔP_{12AM} = 103.73 kW, 37.1%) and loss of adherence of AM ($\Delta P_{connect}$ = 54 kW, 19.3%). The total share of electrical and mechanical power losses in BP is 10% in the consumption of active power motors ($P_{\Sigma AM}$ = 2803.2 kW), which corresponds to an average efficiency of the electric load □pp = 90%. High efficiency is due to the fact that most of the active power consumes AM with a nominal power of more than 100 kW.
- Electric losses of active power in SMs PSS $\Delta P_{\Sigma SM}$ = 278.24 kW are composed of losses in the stator winding (ΔP_{1SM} = 64.06 kW, 23%) and in the excitation winding (ΔP_f = 30.57 kW, 11%), power losses in the steel of the magnetic systems of AM ((ΔP_{12SM} = 145.61 kW, 52.3%) and the loss of connection of the SD ($\Delta P_{connect}$ = 38 kW, 13.7%). The

total share of electrical and mechanical power losses in SD is 4.6% in the consumption of active power motors ($P_{\Sigma AM}$ = 6000 kW), which corresponds to an average efficiency of the electric load η_{av} = 95.4%. The high efficiency is due to active power consumes SMs with a rated output of more than 100 kW.

- From the data obtained by calculation, it follows that the consumption of reactive power decreaPSS with decreasing voltage (from U = 1,1 to U = 0,8 of nominal) at the terminals of transformers T1, T2 TP-26 with a load factor of asynchronous and synchronous motors equal to 0 ,5;

- Consumption of reactive power in AM PSS $\Delta Q_{\Sigma AM}$ = 2.77 MWar consists of losses in stator (ΔQ_{1AM} = 279.02 kVar, 10.07%) and rotary (ΔQ_{2AM} = 327.12 kvar, 11.81%) windings, power losses in the steel of the magnetic systems of AM (ΔQ_{12AM} = 2.16 mVAr, 78.01%) and loss of adherence of AM ($\Delta P_{connect}$ = 2kVar, 0.11%).

4.2 Static power and power losses of the workshop substation of SSGPO JSC

For the study of the static characteristics of power losses, the electric power supply system for the pellet production plant (TSO) of TP-26 substations of SSGPO JSC was chosen with the existing Kl = 0.7 AM and Kl = 0.8 SM, which correspond to the most probable mode of operation of the engines.

Figure 4.28 shows the static characteristics of the total losses of active power in the scheme under consideration with K_l = 0.7 AM and K_l = 0.8 SM. The adopted designations are similar to Figure 4.3.

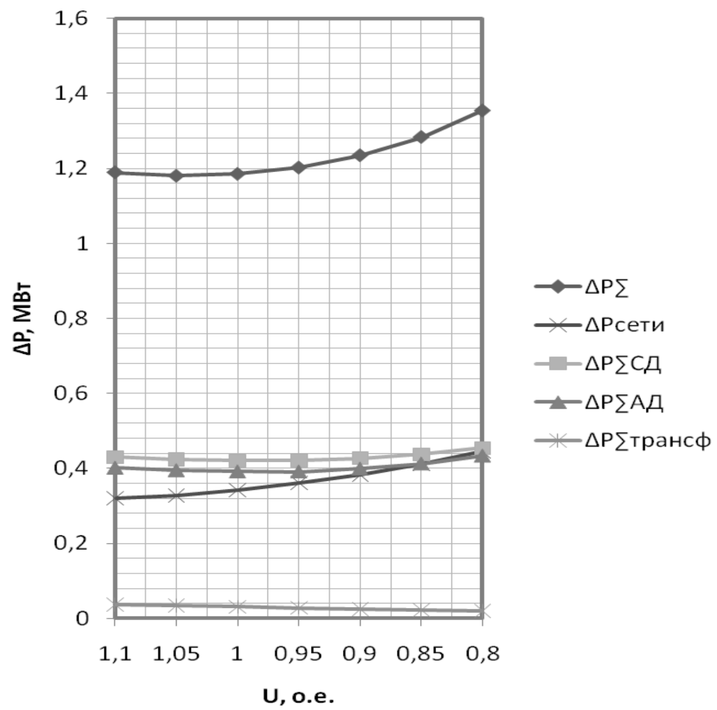


Figure 4.28 - Static loss characteristics active power for TP-26

Figure 4.29 shows the static characteristics of the total losses of the active power of the AM in the scheme under consideration with $K_l = 0.7$. The adopted designations are similar to Figure 4.4.

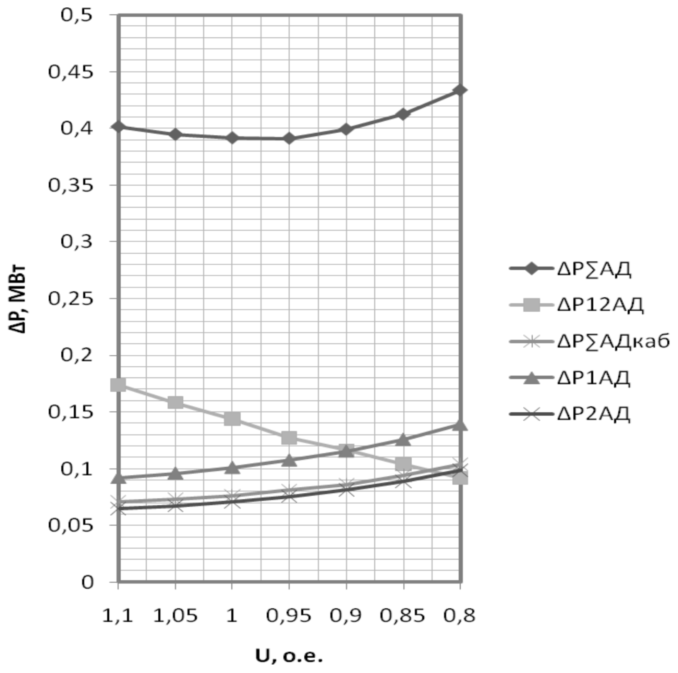


Figure 4.29 - Static characteristics of active power loss in AM

Figure 4.30 shows the static characteristics of the total losses of the active power of the SM in the scheme under consideration with $K_l = 0.8$. The accepted designations are similar to figure 4.5.

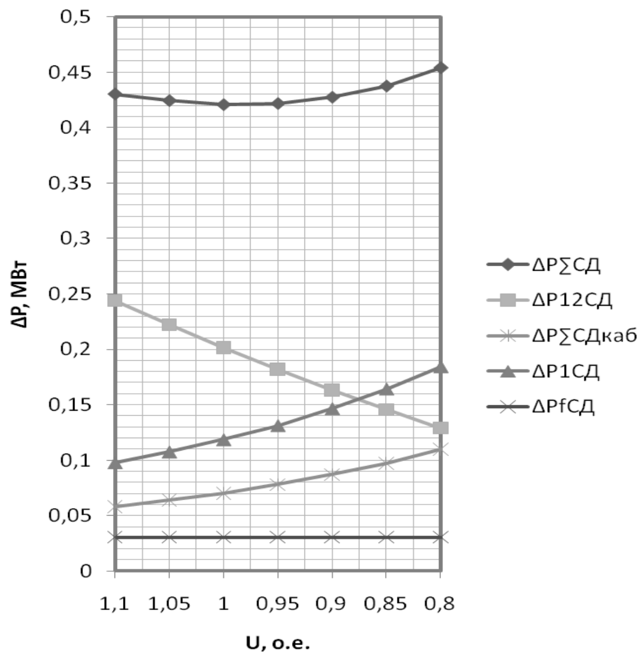


Figure 4.30 - Static Characteristics of Active Power Loss in the SM

Based on the analysis of the static characteristics of power losses in the workshop PSS, we formulate the following conclusions:

- Minimum losses of active power take place at K_l = 0,7AD and K_l = 0,8SM at the voltage at the terminals of transformers T1, T2 ТП-26, equal to the mains voltage (U = 1,05); they are equal to ΔP_{Σ} = 1,180 MW, which is 6.5% of the active power entering transformers T1, T2 (P_{Σ} = 18.02 MW).
- The achieved effect of reducing power losses from voltage regulation on the TP-26 tires within the allowed GOST13109-97 is 55 kW or 5% of the total power loss in PSS, which corresponds to 360 thousand kWh per year with the number of hours of use of the maximum T_{max} = 6550 hour.
- Total losses of active power ΔP_{Σ} = 1179,91kW are made up of power losses in the workshop network ΔP_c = 327 kW, power losses in AM PSS $\Delta P_{\Sigma AM}$ = 394.55 kW, power losses in SDS PSS $\Delta P_{\Sigma SM}$ = 424.29 kW, losses in steel transformers $\Delta P_{\Sigma трансф}$ = 34.07 kW. Thus, the overwhelming share of the total active power losses (about 70%) is the electrical power losses in AM and SM of the PSS.
- Electric power losses in AD PSS $\Delta P_{\Sigma АД}$ = 394.55 kW are composed of losses in the stator (ΔP_{1AM} = 95,93kW, 24,3%) and rotary (ΔP_{2AM} = 67,33 kW, 17,1%) windings, power losses in the steel of the magnetic systems of AM (ΔP_{12AM} = 158.29 kW, 40.1%) and loss of adherence of AM $\Delta P_{connect}$= 73 kW, 18.5%). The total share of electrical and mechanical power losses in BP is 10% in the consumption of active power motors ($P_{\Sigma AM}$ = 3924.48 kW), which corresponds to an average efficiency of the electric load η_{av} = 90%. High efficiency is due to the fact that most of the active power consumes AM with a nominal power of more than 100 kW.
- Electric power losses in SM PSS $\Delta P_{\Sigma SM}$ = 424.29 kW are composed of losses in the stator winding (ΔP_{1SM} = 107.53 kW, 25.3%) and in the excitation winding (ΔP_f = 30.57 kW; 7 , 2%), power losses in the steel of magnetic systems AM (ΔP_{12SM} = 222.19 kW, 52.4%) and the loss of connection of the SM ($\Delta P_{connect}$ = 64 kW, 15.1%). The total share of electrical and mechanical power losses in SD is 4.4% in the consumption of active power motors ($P_{\Sigma AM}$ = 9600 kW), which corresponds to an average efficiency of the electric load η_{cp} = 95.6%. The high efficiency is due to active power consumes SMs with a rated output of more than 100 kW.

4.3 Static power and power losses of the workshop substation of JSC Voskresensk Mineral Fertilizers

Open Joint Stock Company Voskresensk Mineral Fertilizers is one of the four largest Russian enterpriPSS producing phosphorus-containing fertilizers, feed additives, phosphoric and sulfuric acid.

Voskresensk Mineral Fertilizers OJSC is located in the city of Voskresensk, one of the industrial centers of the Moscow Region, 88 kilometers southeast of Moscow. Production assets of the enterprise form a territorially isolated compact complex. The main products produced by JSC Voskresensk Mineral Fertilizers are nitrogen-phosphorus fertilizers, which are used in all types of soils and in the cultivation of various types of crops, mono- and diammonium phosphate. In addition, the company produces phosphoric and sulfuric acids of various grades, salts based on phosphoric acids.

JSC Voskresensk Mineral Fertilizers has capacities for the production of 750,000 tons of monoammonium phosphate (MAP) and diammonium phosphate (DAP), 200,000 tons of ammonia, 300,000 tons of phosphoric acid, and 1,100,000 tons of sulfuric acid per year. The main raw material for the production of the enterprise is apatite, which is currently purchased from third parties.

To confirm the adequacy of the results obtained at SSGPO JSC (the Republic of Kazakhstan) and to identify some general patterns in the nature of static characteristics, similar studies were carried out in the power supply system of the TP-75 shop substation of JSC Voskresensk Mineral Fertilizers (Moscow region) with the existing $K_l = 0,7$ AM, which corresponds to the most likely mode of operation of the engines.

Figure 4.31 shows the design scheme of power supply from the transformer T1 TP-75 (power transformer S_{nom} = 1600 kVA). The total number of PSS elements is 134, including cables (29 connections with a total length of 1500 m, a spread of connection lengths from 10 to 99 m, a spread of cable connection cross-sections from 2 × (3 × 120) to 3 × 2.5 mm2, as well as 27 AM with the total installed capacity of 1110, 28 kW, the average power of the engines is 41.12 kW (five have a capacity of over 100 kW: 250, 160, 132, 2 for 110 kW, the minimum power is 0.8 kW).

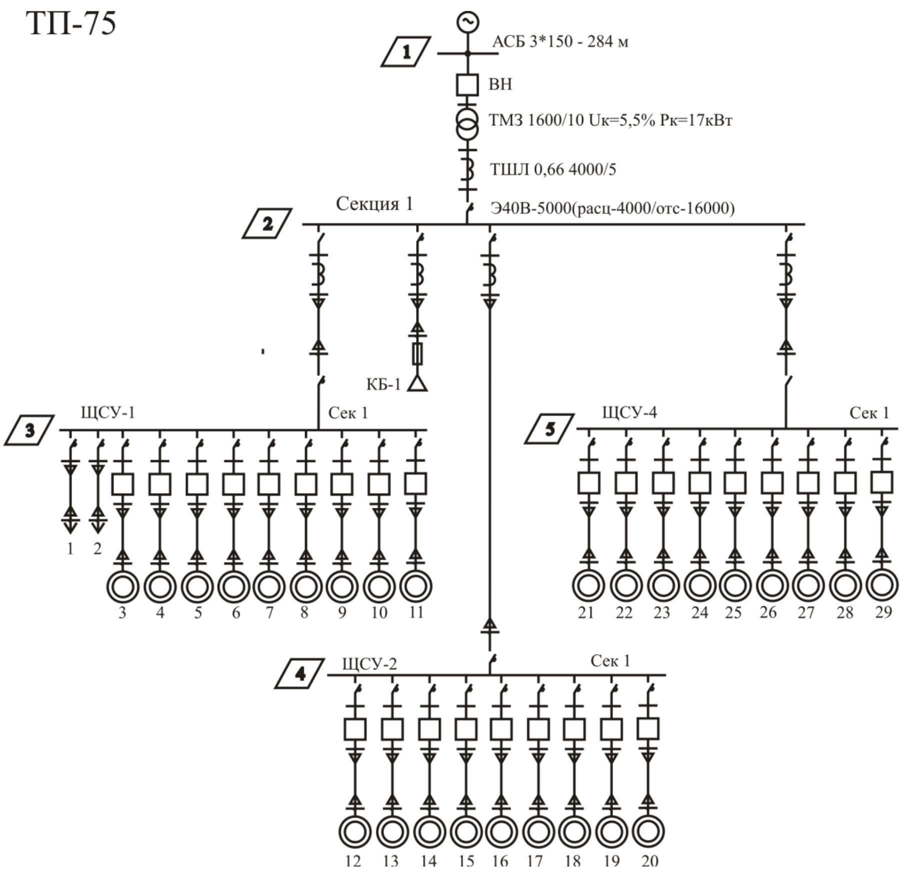


Figure 4.31 - Calculation scheme 1 of section TP-75 of JSC "Resurrection mineral fertilizers"

The other (non-motor) load of 0.38 kV is represented by lighting and welding (the total design capacity is 64 kW, or 7.4% of the total load capacity of the transformer). Also, a battery of capacitors with a capacity of Q_{bk} = 221 kvar

Figure 4.32 shows the static characteristics of the total losses of active power in the circuit under consideration at K_l = 0.7 AM. The adopted designations are similar to Figure 4.3

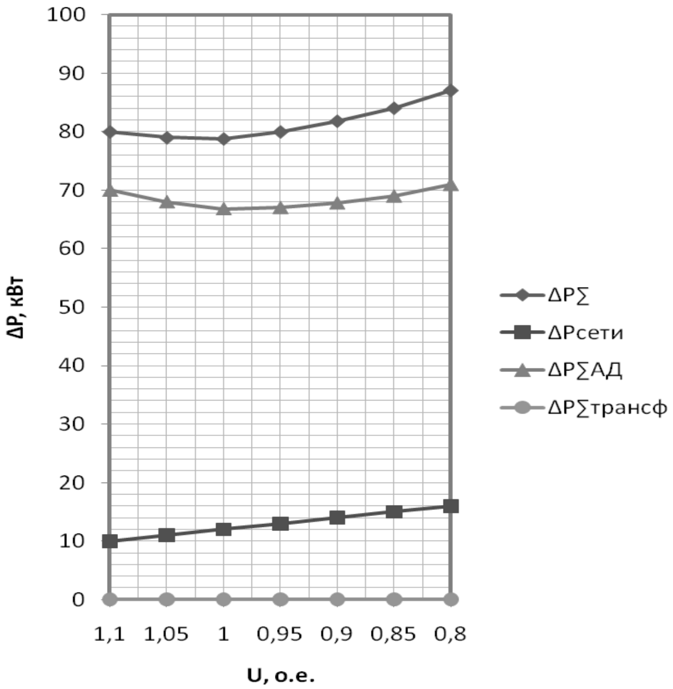


Figure 4.32 - Static Characteristics of Active Power Loss for TP-75

Figure 4.33 shows the static characteristics of the total losses of the active power of the AM in the scheme under consideration with K_l = 0.7. The adopted designations are similar to Figure 4.4.

Based on the analysis of the static characteristics of power losses in the workshop PSS, we formulate the following conclusions:

- Minimum power losses occur when the voltage at the terminals of the transformer T1 TP-75 is equal to the rated line voltage (U = 1); they are equal to ΔP_{Σ} = 78.8 kW, which is 9.1% of the active power entering the transformer (P_{Σ} = 866 kW).
- Total power losses ΔP_{Σ} = 78.8 kW are formed from power losses in the workshop network ΔP_c = 12 kW and power losses in the AM PSS $\Delta P_{\Sigma АД}$ = 66,8 kW. Thus, the overwhelming fraction of the total active power losses (almost 85%) is the electric power losses in the PSS AM
- Electric power losses in AM PSS $\Delta P_{\Sigma AM}$ = 66,8 kW are composed of losses in stator (ΔP_{1AM} = 29,1 kW, 43,6%) and rotary ones (ΔP_{2AM} = 8,5 kW, 12,7%) windings and power losses in the steel of magnetic systems AM (ΔP_{12AM} = 29.2 kW, 43.7%). The total share of electrical and mechanical power losses in AD is 10.2% in the consumption of active power motors ($P_{\Sigma AM}$ = 780.4 kW), which corresponds to an average efficiency of the electric load η_{av} = 89.8%. High efficiency is due to the fact that most of the active power consumes AM with a nominal power of more than 100 kW.

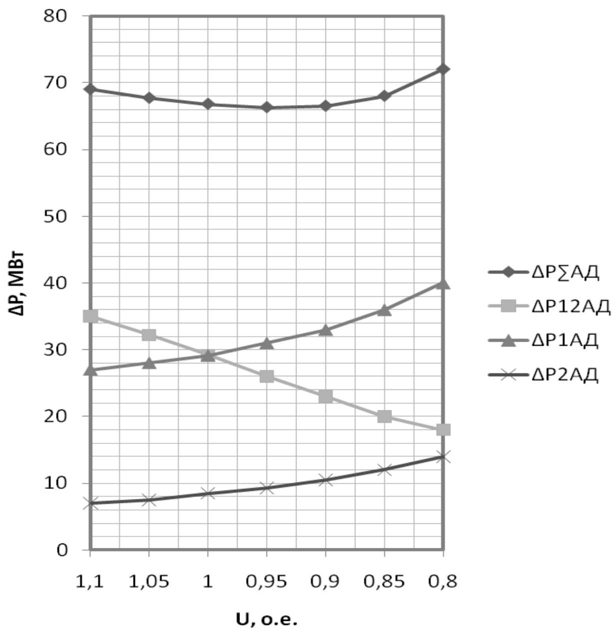


Figure 4.33 - Static characteristics of active power losses in AM

4.4 Conclusions on the chapter

Calculation and experimental studies of the static characteristics of load capacities and active power losses in the power supply system in JSC SSGPO and Voskresensk Mineral Fertilizers allowed the following conclusions:

1. The total losses of active power of in-house PSS are from 6.5 to 9.1% of the power consumption; the share of loss of active power in AM - from 70 to 85% of losses in PSS. The total efficiency of the motor load reaches 89.8-95.6%. This is due to the fact that most of the active power consumes AM and SM with high efficiency (Rn> 100 kW).

2. Minimum power losses at existing load factors of AM and SM of PSS TP-75 (JSC Voskresensk Mineral Fertilizers take place at the voltage at the terminals of the transformers equal to the rated voltage of the network, and for TP-26 (SSGPO) - at (U = 1.05) of the nominal. The effect of voltage regulation on the TP-26 and TP-75 tires within the permissible GOST-13109-97 values will help reduce unproductive power losses.

3. When the load factor of the AM and SM was changed, it was established that the minimum losses of active power take place at different voltage values at the terminals of the transformers T1, T2 TP-26 (SSOPSO), so at KL = 0.9 are equal to the line voltage (U = 1,1) of the rated voltage, and at Ks = 0,8, equal to the mains voltage (U = 1,05) of the rated voltage, and at KL = 0,7, equal to the rated voltage of the network (U = 1), appris = 0.6 are equal to the mains voltage (U = 0.95) of the rated voltage, and for KL = 0.5 they are equal to the mains voltage (U = 0.85) of the rated voltage.

4. In the active load, the overwhelming fraction of 70 to 90% is the power consumed by the AM and SM, so the consumption of active power is significantly dependent on the voltage at the terminals of the transformers of the shop TP. With a decrease in voltage by 10%, the active power consumption of AM decreaPSS by 3-5%.

THE CONCLUSION

The theoretical and calculation-experimental studies carried out make it possible to formulate the following conclusions:

1. The methodology, algorithm and program for calculating the parameters of the replacement circuit and starting characteristics, low-voltage and high-voltage AMS with respect to the determination the developed of the static characteristics of power losses.

2. The methodology, algorithm and program for calculating the parameters of the substitution circuit and the starting characteristics of the SM with bonded poles and a massive smooth rotor have been developed with reference to the determination of the static characteristics of power losses.

3. Based on the developed techniques, algorithms and programs, the SEZAM software package for calculating steady-state PSS regimes was designed to perform a comprehensive evaluation of the effect of voltage regulation on substation buses on the level of total power losses in all elements of the power supply system.

4. Based on the computational studies of the static power losses characteristics of electric motors, it is determined that the minimum of active power losses in AMSs, SMs with bonded poles and a massive smooth rotor essentially depends on their loading and changes when the load factor varies from 1 to 0.5 within the voltage range from 1,1 to 0,65 of the nominal.

5. Calculation studies of static power characteristics for real industrial facilities showed that in the structure of electrical losses in PSS, power losses in electric motors with existing load factors of AM and SM are 70% for JSC SSGPO, TP-26 and 85% for JSC " Voskresensk mineral fertilizers ", TP-75 and depend on the composition of the loads and their unit capacity.

6. The SEZAM software package was used in the work on the development of energy saving measures for JSC SSGPO (the Republic of Kazakhstan) by determining the optimal voltage levels in order to minimize power losses. It has been established that the effect of reducing losses as a result of voltage regulation on the bus bars of the substation PT-26 within the limits allowed by GOST 13109-97 may amount to 55 kW or 5% of the total power losses in PSS, while reducing unproductive electricity consumption - 360,250 kWh per year or in monetary terms 2700 thousand tenge with the number of hours of use of the maximum T_{max} = 6550 hours.

DEFINITIONS

This monograph use the following terms with the corresponding definitions:

An asynchronous motor is an AC electric machine whose rotor speed is not equal (in the driving mode less) to the frequency of rotation of the magnetic field created by the current of the stator winding.

The unified energy system is a set of interconnected power systems connected by intersystem connections, covering a significant part of the country's territory in the general operating mode and having a dispatch control

Energy quality is a system of indicators established by state standards or other normative acts that confirms consumer properties and the availability of energy for consumption.

Reliability of the energy system - the ability of the power system to ensure the continuity of energy supply to consumers and maintaining within the allowed limits of electricity and heat.

The quality standard of electric energy is the established limiting value of the quality index of electric energy.

The power supply system is a system united by a common process of generating and (or) transforming, transmitting and distributing electric energy and consisting of sources and (or) converters of electrical energy, electrical networks, switchgears, and devices that maintain its parameters within specified limits.

The united energy system is a set of several energy systems united by a common operating mode, having a general dispatching control as the highest degree of control in relation to the dispatching control of the power systems entering into it.

Load of the consumer - the value of the power or amount of heat consumed by the power plant at a specified time

Nominal voltage is the voltage for which the electrical network is designed or identified, and in relation to which its operating characteristics are set.

The indicator of the quality of electric energy is a quantity characterizing the quality of electric energy by one or several of its parameters.

The reliability index is a quantitative characteristic of one or several properties that make up the reliability of an object.

Losses - the difference between the power consumption and the useful power of any system or device.

The consumer of electric energy is an enterprise, an organization, a territorially grounded shop, a construction site, an apartment in which the receivers of electrical energy are connected to the electric grid and use electric power.

Software - a set of programs performed by the computer system.

A synchronous motor is an AC electric machine whose rotational speed is equal to the frequency of rotation of the magnetic field in the air gap.

Static power characteristics of the load node - the dependence of the active P (U) and reactive Q (U) load powers on the voltage in the load node

Management is any change in the state of an object, system or process leading to the achievement of the goal.

Stability of the power system - the ability of the power system to return to the established mode of operation after various kinds of disturbances.

Electrification - the introduction of electrical energy in the national economy and everyday life.

Electrical safety - a system of organizational and technical measures and means to protect people from harmful and dangerous effects of electric current, electric arc, electromagnetic field and static electricity.

Power transmission - a set of power lines and substations intended for the transmission of electrical energy from one region of the power system to another.

Energy - the area of the national economy, science and technology, encompassing energy resources, production, transmission, conversion, accumulation, distribution and consumption of various types of energy

The energy system is a set of electric stations, electric and heat networks connected to each other and connected by a common mode in the continuous process of production, transformation and distribution of electric energy and heat, with the overall management of this system.

NOTIONS AND ABBREVIATIONS

ATS - Automatic Transfer Switching
AM - asynchronous motor
AMS - asynchronous motor with squirrel cage induction
JSC "SSGPO" - joint-stock company "Sokolov-Sarbai Mining and Production Association";
AR - Auto reclosure
SD - switching devices
CE - coefficient of efficiency
IE - industrial enterpriPSS;
RK - Republic of Kazakhstan;
SG - Switchgear
SM - synchronous motor
SMMR - synchronous motor with a massive smooth rotor
SMSP - synchronous motor with bound poles
IPSS - industrial power supply system
PSS - power supply system;
TS - transformer substation
TPS-Thermal power station;
WPP - workshop for the production of pellets;
EMF - electromotive force
EE is the electrical energy;

The work uPSS traditional units for electricity supply literature: AV Om, kV, s, km, mm2, kW, kVar, kVA.

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