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Methods for determining static characteristics in industrial electrical networks

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Abstract. The article considers the influence of voltage quality on the efficiency of electrical networks and electrical receivers. The economic characteristics of consumers and load nodes and methods of their construction are given. The construction of static characteristics of load nodes is considered by analyzing the mathematical model of the node and using the results of a passive experiment and the possibility of estimating the stability reserve, total power and energy losses and constructing economic characteristics by voltage from them.

1 Introduction

The static characteristics of the load nodes *(UN)* are the dependences of their input active and reactive capacities on voltage. These characteristics are determined in the range of permissible voltage changes at the terminals of U_N $U = (0.9\text{-}1.1)\ U_n$. The form of these characteristics depends on the configuration of the power supply network, the number of energy transformations and the composition of consumers, lighting, etc. Static characteristics *P(U), Q(U)* can be set graphically and analytically, and often have a V-shaped, nonlinear shape, contain valuable information about the *UN*. They are necessary for determining the active and reactive capacities in the node and their losses, for constructing economic characteristics, calculating the static stability of the *UN,* etc [1-6, 8]. Static characteristics of *UN* can be determined by the following methods: analytical; method of active experiment, method of passive experiment. In a particular case, the *UN* can be bipolar, i.e. it has a one-way power supply. The analytical method is based on the known composition of the node load-the scheme of the power supply system and the number of energy consumers. At the same time, a replacement scheme of the *UN* is drawn up, for which the dependences of active and reactive power on voltage are determined, according to which it is possible to build the most graphs [7-15, 18]. The analytical method also makes it possible to study the parameters of the design scheme, as well as the quantitative composition of energy consumers for static characteristics *P(U), Q(U).* This method is applicable at the operational level, if it is possible to determine the composition of the load with acceptable accuracy.

2 The current state of the investigated problem

To construct the static characteristics of the *UN* by the method of active experiment, it is necessary to be able to regulate an independent variable, the voltage at the input terminals of the load node in the permissible range (0.9-1.1) U_n, and for each value of U to record the steady-state values of *P* and *Q*. When conducting experiments, it is necessary to observe the conditions so that all other factors affecting *P, Q* are absent or minimal compared to the influence of U. To weaken the influence of side factors, experiments are carried out during the period of practical stationary operation of the *UN*. The period of stationary capacity *P, Q* can be determined by a static survey of load schedules *P(t), Q(t)* for typical days (working and non-working days). Thus, the influence of all other factors on *P, Q*, except voltage, is excluded, and 8-10 values of *P, Q* are recorded when adjusting U in the interval (0.9-1.1) U_n. These points have a random spread around the desired actual dependence *P(U), Q(U),* and therefore finding a static characteristic for these experimental points is performed by methods of mathematical statistics, for example, the least squares method. At the same time, "smoothing" is performed at the beginning and then an analytical expression of the desired curve is given, the coefficients of which are determined by the least squares method or by methods of minimizing a nonlinear function with an estimate of the approximation error [16-22, 9, 10]. The construction of

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statistical characteristics of the *UN* by the active method is complicated by the regulation of voltage at the input terminals in the interval (0,9-1,1) U_{nom} and difficulties in constructing characteristics for all necessary modes and structure of the load node. When constructing the static characteristics of the *UN* by the method of passive experiment, there is no need to adjust the voltage at the input terminals of the UN. At the same time, changes in *U, P, Q* are isolated and recorded in the normal stationary mode of operation of the unit. Studies show that stresses with a period of several minutes are created by random phenomena in the system that are external to the *UN*, so they can be considered as disturbances at the terminals of the *UN, P, Q*-as a reaction of the *UN* to these disturbances. Thus, by measuring averaged over a time interval of values of ΔU, ΔP, ΔQ, we find the regulatory effects $k\_p=\Delta P/\Delta U$ and $k\_Q=\Delta Q/\Delta U$. Quantitatively, ΔU, ΔP, ΔQ is about one percent of the basic values of these quantities, and their slow changes practically do not cause dynamic processes in the *UN*. According to the known values of the powers P, Q and the regulating effects *k_p, k_Q*, it is possible to determine the static characteristics of the UN by determining the parameters of the substitution scheme of the UN by synthesis methods or using the known regression equations [23-25, 5] $k_p, Q_p\ c\ k'_p, k'_Q$.
where $k'_p = \frac{d^2p}{dU^2}$; $k'_Q = \frac{d^2Q}{dU^2}$

As noted, the shape of the experimental curves of static characteristics *P(U)*, *Q(U)* is similar to V-shaped lines. Analytically, these curves in the range of permissible voltage variation $(0{,}9\div1{,}1)\cdot U_n$ can be approximated by: second-order polynomials; dependencies corresponding to the selected structure of the substitution scheme of the UN. Second - order polynomials:

$$P = P_0(a_0 + a_1k_u + a_2k_u^2) \quad (1)$$

$$Q = Q_0(b_0 + b_1k_u + b_2k_u^2) \quad (2)$$

where $k_u=U/U_0$; U_0, P_0 〖Q〗 0 are the values of voltage, active and reactive power at the input terminals of the *UN* in the initial normal mode; P, Q are the current power values corresponding to the current voltage values.

For a particular *UN*, the coefficients of the polynomials are determined based on the experimentally obtained static characteristics by the least squares method. To satisfy the conditions for passing polynomials through the points $P(U_0)=1$ *u* $Q(U_0)=1$, it is necessary to observe the conditions of restriction $a_0+a_1+a_2=1$, $b_0+b_1+b_2=1$. Substituting these conditions in (1), (2), we get

$$\frac{P}{P_0} = 1 - a_1(1-k_u) - a_2(1-k_u^2);$$

$$\frac{Q}{Q_0} = 1 - b_1(1-k_u) - b_2(1-k_u^2).$$

Using the experimental points of static characteristics, we find the coefficients a_1 a_2, b_1 b_2 of these expressions, and then a_0 and b_0. The standard error of the approximating curves (1), (2) is determined from the expressions.

$$\sigma_p = \sqrt{\frac{\sum_1^n(P_e-P_p)^2}{n}}; \qquad \sigma_Q = \sqrt{\frac{\sum_1^n(Q_e-Q_p)^2}{n}},$$

where *P_e,Q_e,P_p,Q_p* are experimental and calculated power values; n is the number of experimental points.

Based on the values *σ_p* and *σ_Q,* a conclusion is made about the admissibility of using approximating expressions (1), (2). Below are some recommended values of the coefficients a_i 〖,b〗 _i [3] Approximate values:

$$P = P_0(0{,}83 - 0{,}3k_u + 0{,}47k_u^2); \quad (3)$$

$$Q_{NOkV} = Q_0(3{,}7 - 7k_u + 4{,}3k_u^2); \quad (4)$$

$$Q_{6kV} = Q_0(4{,}9 + 10{,}1k_u + 6{,}2k_u^2). \quad (5)$$

$$Q = Q_0(5{,}6 - 12{,}3k_u + 7{,}7k_u^2););\quad (6)$$

$$Q = Q_0(6{,}7 + 15{,}3k_u + 9{,}55k_u^2) \quad (7)$$

when $\cos\varphi_0=0{,}85$. The polynomial approximation of static characteristics is the discrepancy of such an expression to the physical content of processes in the *UN*. Extrapolation of these characteristics by other voltage values, e.g. lower and higher for tuning purposes anti-accident automation, as well as for the decomposition of capacities into the main components for economic calculations by polynomials, is not possible. Analytical expressions of static characteristics corresponding to the physical meaning of the processes are more suitable in *UN*.

3 Definition of critical elements in energy systems

In most cases, the complex load of the *UN* consists of a combination of asynchronous, synchronous motors and passive load (furnaces, lighting, welding, etc.). These three equivalent elements can be taken as a replacement scheme (Fig. 1).

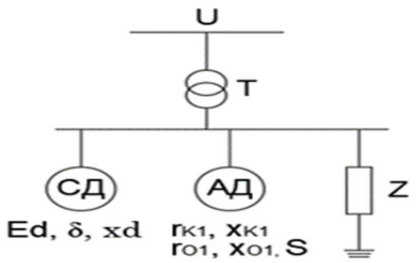

Fig.1. Scheme of asynchronous and synchronous motors and passive load

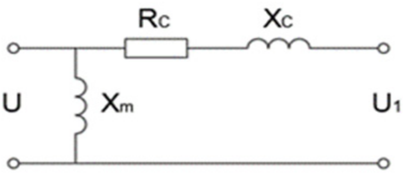

Fig.2. Scheme branch magnetization network transformers

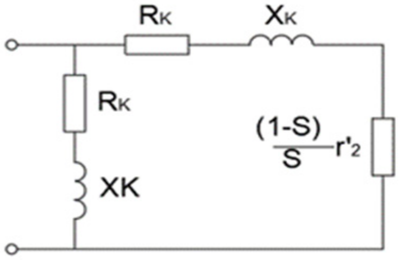

Fig.3. Scheme of asynchronous load with " G" figurative equivalent circuit

In general, the supply network has a complex configuration with many stages of energy transformation and can be represented by an L-shaped circuit with a longitudinal equivalent resistance $Z_c=R_c+jX_c$ and a transverse reactance X_m, which is a branch of magnetization of network transformers (Fig.2).

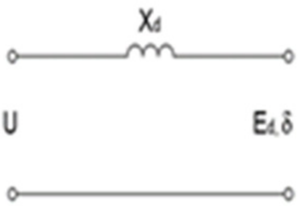

Fig.4. Scheme with synchronous resistance X_d and EDF E_d

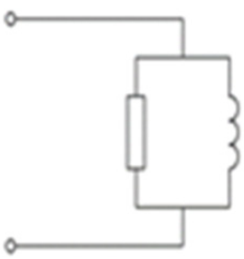

Fig.5. Scheme Circuit passive resistance load Z_n

In turn, the asynchronous load is represented by an L-shaped replacement circuit (Fig.3), the synchronous load is represented by resistances x_d and EMF E_d (Fig.4), and the passive load is represented by resistance Z_n, consisting of parallel connected $R_{(n)}$ and X_p (Fig.5). Then the equivalent substitution scheme (Fig.1) for the UN will correspond to the following analytical expressions of the powers P,Q at the output terminals of the UN.

$$P = P_{ном}\left(\frac{1-\frac{S_{ном}}{k_u^{\alpha}}}{1-S_{ном}}\right)^{\beta_н} + P_{сн} + P_n k_u^{\alpha} + \frac{\Delta P_{In}}{k_u^2} + \Delta P_{On} k_u^{\alpha_1}; \quad (9)$$

$$Q = Q_{On}k_u^4 - Q_{1C}\left(\frac{k_u^4-b^2}{1-b^2}\right)^{0,5} + Q_{2C}k_u^4 + Q_n k_u^2 + \frac{\Delta Q_{In}}{k_u^{\alpha}} + \\ +\Delta Q_{On}k_u^{\alpha_1}. \quad (10)$$

Where *P_IH, P_*sn are the useful power on the shaft of equivalent asynchronous and synchronous motors at rated voltage; *P_n, Q_n* are the active and reactive power consumed by an equivalent passive element at rated voltage; *P_OH,Q_OH* - active and reactive magnetization power of an equivalent asynchronous motor at rated voltage; Δ*P_OH*,Δ*Q_OH* - active and reactive load losses caused by the magnetization current of an equivalent asynchronous motor at rated voltage; Δ*P_IH*,Δ*Q_IH*- active and reactive load losses caused by the load currents of equivalent asynchronous and synchronous motors; *Q_1C,Q_2C*- reactive power of an equivalent synchronous motor generated and consumed at rated voltage; α,α1- coefficients; *α=2:4,α_1=2:6; β_n* is the coefficient characterizing the moment of resistance of the driven mechanism; b is the coefficient taking into account the influence of the degree of loading and the excitation current of the synchronous load, is the sliding of an equivalent asynchronous motor at rated voltage. All powers are expressed relative to their values at U_n [4].

4 Conclusion

The advantage of the load node models in the form of (9) and (10) is the possibility of determining the component capacities depending on the voltage, the possibility of synthesizing the parameters of equivalent elements replacement circuits for calculating the dynamic characteristics of the load node. All this is very important when solving problems in the field of optimizing the quality of the voltage of the network (node) and finding critical voltages for analyzing the stability of the *UN* operation. It is obvious that for a given static characteristic of *UN*, if necessary, it is possible to switch from the analytical form of polynomials to dependencies (9) and (10).

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