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Calculation of Load Losses of Electric Energy by the Probabilistic-Statistical Method

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ABSTRACT: This article presents the main provisions of the probabilistic-statistical method based on probabilistic flow distribution for calculating electrical energy losses, taking into account the correlation dependencies between the capacities of nodes, and a model of power consumption is proposed that describes the initial data for the load nodes of the electrical network for daily, monthly and annual time intervals. The probabilistic-statistical method of calculating load losses of electrical energy removes the main assumption of traditional methods – the introduction of the same integrating factor in the loss formula for all elements of the electrical network, and also allows you to take into account the heterogeneity of the loads of network nodes and correlations between the capacities of the loads of nodes.

KEYWORDS: electrical networks, electrical energy, losses, probabilistic-statistical method, probabilistic flow distribution, power loss calculations, correlation between node loads, daily load curves.

I.INTRODUCTION

The calculation of electrical energy losses has always come up against the lack of complete and to some extent reliable information about the graphs of electrical loads, the amount of electrical energy consumed by the nodes of the network diagram, the switching states of the electrical network diagram, etc.
Modern automated information-measuring systems gradually remove this problem and allow you to determine the loss of electrical energy at the pace of the process for short time intervals. However, in many cases, the calculation of load losses still requires certain changes, additions, substitutions and assumptions to complete part of the information about the modes of consumption of electrical energy for the calculated time interval.
At the same time, the resulting model of power consumption can be used to calculate losses both for the past time intervals of the operation of electrical networks (in fact) and for future (forecast) intervals [1,2].
All practical methods for calculating the load losses of electrical energy (hereinafter referred to as the loss forecast) have the main assumption based on making some so-called integrating factor the same for all elements of the network design scheme. [3]
In this case, to evaluate the integrating factor, the load graph of the power supply center of the electrical network or the total graph of the main consumers in the network is used. This greatly simplifies the calculation of losses and the accuracy of the calculation can be improved, for example, by increasing the number of time intervals into which the main calculation interval is divided. Each interval has its own integrating factor. This approach is acceptable for relatively homogeneous (similar in configuration) consumer load curves and a radial-main (open) circuit of an electrical network.
This paper presents the main provisions of the calculation of electrical energy losses by the probabilistic-statistical method (PSM), in which there are no common integrating factors and some assumptions adopted in traditional methods.

II.RESEARCH METODOLOGY

1. Calculation of losses of electrical energy according to the probabilistic-statistical method (VSM) is carried out according to the formula

$$\Delta \mathbf{W} = \mathbf{M}\,[\Delta \mathbf{P}]\mathbf{T}\mathrm{p} \qquad (1)$$

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where M[ΔP] is the mathematical expectation of power losses or average power losses ΔP_{cp} in the electrical network; Tr is the estimated period of time. Calculation of average losses along the high-speed lines for one branch of the network scheme is performed according to the formula [2]

$$M\left[\Delta P_{ij}\right] = G_{ij}\left[\left(m_{U_i'} - m_{U_j'}\right)^2 + D_{U_i'} + D_{U_j'} - 2cov\left(U_i', U_j'\right) + \left(m_{U_i''} - m_{U_j''}\right)^2 + D_{U_i''} + D_{U_j''} - 2cov\left(U_i'', U_j''\right)\right] \quad (2)$$

where i, j are the numbers of nodes adjacent to the branch; Gij is the active conductivity of the branch (the real part of the conductivity complex obtained as the reciprocal of the resistance complex of the branch); U', U" are the real and imaginary components of the complex of stresses at the nodes, marked with indices of node numbers i and j; m and D are the symbols of the mathematical expectation and variance of the variable written as their indices.

The total average power losses in the network are defined as the sum of the average losses for all branches of the network diagram. A similar approach to the calculation of electrical energy losses is described in [1].

Thus, the calculation of the average power losses is preceded by the calculation of the mode of the electric network in a probabilistic setting (probabilistic (flow distribution) - the calculation of mathematical expectations and voltage covariances of the nodes of the electric network [6–10].

The mathematical model of the steady state of the electric network, consisting of n nodes, for the numerical characteristics of the powers (initial data) and voltages at the nodes (desired values) for the probabilistic-statistical is written in the form [2]

$$\sum_{j=0}^{n-1}\left\{\begin{matrix} G_{ij}\left[m_{U_i'}m_{U_j'} + cov\left(U_i', U_j'\right)\right] - B_{ij}\left[m_{U_i'}m_{U_j''} + cov\left(U_i', U_j''\right)\right] + \\ +B_{ij}\left[m_{U_i''}m_{U_j'} + cov\left(U_i'', U_j'\right)\right] + G_{ij}\left[m_{U_i''}m_{U_j''} + cov\left(U_i'', U_j''\right)\right] \end{matrix}\right\} = m_{P,i}$$

$$\sum_{j=0}^{n-1}\left\{\begin{matrix} -B_{ij}\left[m_{U_i'}m_{U_j'} + cov\left(U_i', U_j'\right)\right] - G_{ij}\left[m_{U_i'}m_{U_j''} + cov\left(U_i', U_j''\right)\right] + \\ +G_{ij}\left[m_{U_i''}m_{U_j'} + cov\left(U_i'', U_j'\right)\right] - B_{ij}\left[m_{U_i''}m_{U_j''} + cov\left(U_i'', U_j''\right)\right] \end{matrix}\right\} = m_{Q,i} \quad (3)$$

where and are the mathematical expectations of the powers in the network nodes; Gij and Bij are elements of the matrix of nodal conductivities (active and reactive components); , - $m_{U_i'}, m_{U_j'}$ $m_{U_i''} m_{U_i''}$ mathematical expectations of the real and imaginary components of stress complexes at nodes i and j;

$$cov\left(U_i', U_j'\right), cov\left(U_i', U_j''\right), cov\left(U_i'', U_j'\right), cov\left(U_i'', U_j''\right) \quad (4)$$

are the covariances between stress components at nodes i and j, and

$$\mathbf{Jcov}\left(\mathbf{U_i'}, \mathbf{U_j''}\right)\mathbf{JT} = \mathbf{cov}(\mathbf{P}, \mathbf{Q}) \quad (5)$$

where J is the Jacobian matrix of the system of equations (3); the covariance matrix of the components of the stress complexes at the nodes; cov(P,Q)-covariance matrix of powers in nodes, calculated for the calculation period Tp.

2. Power consumption model

The initial data for the calculation, in addition to the network parameters, are mathematical expectations and the covariance matrix of powers in the nodes. These two elements make up the model of power consumption for the estimated time interval in the calculated network.

The system of equations (3), (4) is solved simultaneously, as a result of which the mathematical expectations and the covariance matrix of the components of the stress complexes at the nodes are obtained. They are necessary to calculate the losses of electricity according to formulas (1) and (2).

It should be noted that equations (2)–(4) are written in terms of real and imaginary components of voltages at network nodes U', U" in the so-called form of Cartesian coordinates of the representation of vectors of complex variables of steady state equations.

This allows you to write equations for mathematical expectations (2) and (3) quite correctly without using the linearization technique, which is impossible when using the polar form of writing equations.

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The change in the loads of the electrical system over time is interconnected due to cyclic patterns due to daily, weekly and annual periods.
Weekly periods are characterized by reduced consumption of electrical energy on weekends. The presence of holidays also changes the power consumption and the configuration of the daily load curves. The annual period for most loads is characterized by a summer decrease in power consumption.
To calculate the losses of electrical energy for the estimated time interval Tr equal to days, months or years, one should take into account not only changes in each load separately, but also stochastic relationships between them.
In the case of full measurements of load powers with a given discreteness in time for the entire interval Tp in each node of the electrical network, the power consumption model is obtained without introducing special conditions and according to known formulas for mathematical expectations and the covariance matrix of node powers for a statistical sample of size N .
It is acceptable and correct to perform N calculations on average hourly load data. This approach is used in the presence of automation of measurements at the pace of the process.
Consider one of the possible models of power consumption. To do this, several assumptions must be made. First, consider one load node of the electrical network and the estimated interval Tr, equal to one month.
On the basis of measurements or according to typical load schedules of consumers connected to the network node, we will determine the characteristic daily load schedule of a working and non-working day. Let's take these schedules the same for the corresponding days of the entire billing month, we will have np working and nn non-working daily load schedules (np + nn = n - the number of days in a month).
For the power consumption model, it is necessary to obtain mathematical expectations and load power dispersions for the calculated interval. For daily time intervals, numerical characteristics are obtained from samples of 24 values for working mp, Dp and non-working mn, Dn days.
The numerical characteristics of the load power of the monthly interval mm, Dm will be determined through the numerical characteristics for the daily intervals. This can be done according to the monthly schedule of average hourly power values, compiled from np and nн daily graphs, or by the formulas

$$\mathbf{m_{м} = \frac{n_p m_p + n_{н} m_{н}}{n}\ ;\ D_{м} = \frac{n_p D_p + n_{н} D_{н}}{n} + D_{м(c)}}. \qquad (6)$$

where Dm(s) is the load power dispersion for a monthly interval, obtained from a sample of n average daily values (mathematical expectations for daily intervals).
If we convert the monthly graph of average daily values into a graph by duration, then we get a two-stage graph, one step with a value of mp with a volume of np working and another mn with a volume of nn values. Then we will have

$$\mathbf{D_{м(c)} = \frac{\sum_{i=1}^{n} m_{c,i}^2}{n} - m_{м}^2 = \frac{n_p m_p^2 + n_{н} m_{н}^2}{n} - m_{м}^2} \qquad (7)$$

where m c,i is the mathematical expectation of the load power for the i-th day.
Thus,

$$\mathbf{m_{м} = \frac{n_p m_p + n_{н} m_{н}}{n};\ D_{м} = \frac{n_p D_p + n_{н} D_{н}}{n} + \frac{n_p m_p^2 + n_{н} m_{н}^2}{n} - m_{м}^2} \qquad (8)$$

If we imagine that for all 12 months of the year m m, i, D m, i (i = 1,2, ..., 12) are obtained, then for the calculated interval equal to a year, the variance can be determined from the variances of all twelve months, taking into account their difference in number of days:

$$\boldsymbol{m_{г} = \frac{\sum_{i=1}^{12} n_i m_{м,i}}{n_{г}}\ ;\ D_{г} = \frac{\sum_{i=1}^{12} n_{м,i} D_{м,i}}{n_{г}} + D_{г(м)}} \qquad (9)$$

where Dm,i is the dispersion of the load power for the i-th month; D g (m) - the dispersion of the load power for the year, calculated from the average monthly values; ng is the number of days in a year.
It was shown in [11] that, assuming the same variances of the daily load schedules, as well as the same variances of the monthly schedules, the variance of the annual schedule can be obtained as the sum

$$\mathbf{D_{г} = D_{c} + D_{м(c)} + D_{г(м)}} \qquad (10)$$

where Dc is the dispersion of the daily load schedule; Dm(s) - load power dispersion for a monthly interval, calculated from average daily values; D g (m) - the dispersion of the load power for the year, calculated from the average monthly values.
Relations (6)–(8) make it possible to obtain the dispersion of the annual load schedule for different daily schedules by months of the year.
The power consumption model for several nodes also includes covariances between node load powers. To determine the node power covariance matrix for the annual period, it is also possible to use relations (6)–(8):

$$cov(\mathbf{P}_{\text{г}}, \mathbf{Q}_{\text{г}}) = \frac{1}{\mathbf{n}_{\text{г}}} \sum_{i=1}^{12} \mathbf{n}_{\text{м},i} \mathbf{cov}(\mathbf{P}_{\text{м},i}, \mathbf{Q}_{\text{м},i}) + \mathbf{cov}(\mathbf{P}_{\text{г(м)}}, \mathbf{Q}_{\text{г(м)}});$$

$$\mathbf{cov}(\mathbf{P}_{\text{м},i}, \mathbf{Q}_{\text{м},i}) = \frac{1}{\mathbf{n}_{\text{м},i}} \left(\mathbf{n}_{p,i} \mathbf{cov}(\mathbf{P}_{p,i}, \mathbf{Q}_{p,i}) + \mathbf{n}_{\text{н},i} \mathbf{cov}(\mathbf{P}_{\text{н},i}, \mathbf{Q}_{\text{н},i})\right) + \mathbf{cov}\left(\mathbf{P}_{\text{м(с)},i}, \mathbf{Q}_{\mathbf{P}_{\text{м(с)},i}}\right),$$

$$\mathbf{cov}\left(\mathbf{P}_{\text{м(с)},i}, \mathbf{Q}_{\mathbf{P}_{\text{м(с)},i}}\right) = \frac{1}{\mathbf{n}_i} \left(\mathbf{n}_{p,i} \mathbf{m}_{p,i} \mathbf{m}_{p,i}^T + \mathbf{n}_{\text{н},i} \mathbf{m}_{\text{н},i} \mathbf{m}_{\text{н},i}^T\right) - \mathbf{m}_{\text{м},i} \mathbf{m}_{\text{м},i}^T \quad (11)$$

where cov(Pg ,Qg) is the covariance matrix of load powers for the annual calculation interval; cov(Pm,i ,Qm,i) is the covariance matrix of load powers for the i-th month; cov(Pg(m) ,Qg(m)) is the covariance matrix of load powers for the annual interval, obtained from average monthly values; cov(Pp,i ,Qp,i) and cov(Pн,i ,Qн,i) – covariance matrices of load powers, respectively, of working and non-working days of the i-th month; cov(Pm(s),i ,Qm(s),i) is the covariance matrix of load powers for the i-th monthly interval, obtained from average daily values; mp,i ,mn,i ,mm,i – vectors of mathematical expectations of load powers, respectively, of working and non-working days and of the entire i-th month.

III. CONCLUSION

Studies performed on the basis of experimental calculations of various schemes of electrical networks [12] show a significant reduction in the error in calculating losses by high-speed lines compared to the average load method. At the same time, the calculation results show

a significant influence of the so-called displacement of the mathematical expectation of the voltage in the nodes due to the use of second-order central moments in the equations of the steady state, equation (3).

Conclusion. The probabilistic-statistical method for calculating the load losses of electrical energy removes the main assumption of traditional methods - the introduction of the same integrating factor in the loss formula for all elements of the electrical network. It also allows to take into account the heterogeneity of the loads of the network nodes, correlations between the capacities of the loads of the nodes and calculate the mathematical expectations of power losses during reverse power and energy flows along the power lines.

This method can be used to improve the accuracy of calculating losses at the rate of the process at hourly and half-hour intervals to take into account changes in power flows across network elements at these intervals.

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