Specific aspects of calculating electrical energy losses in electricity networks

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Abstract. The paper present modes of operation of 10(6) kV distribution networks, which are determined by the loads of consumers. The network scheme is based on an open circuit, which allows you to perform calculations for each 10(6) kV distribution line (feeder) separately. The calculation of power losses in the electric network is carried out by the method of average loads. The paper determines the integral characteristics of the operational parameters of the head branch, determines the parameters of the equivalent power loss of the feeder equivalent circuit, and the equivalent circuit determines the energy loss in the feeder. The paper compiles the equivalent circuit of the considered network section, calculated the parameters of the equivalent circuit elements and determines the total power loss in all linear sections. The paper presents an algorithm for calculating the steady state using the example of a feeder and shows the sequence of calculation of current distribution in the branches of the equivalent circuit.

1. Introduction
The volume of operational information for calculating technical losses in 10(6) kV networks is significantly less than in 110-35 kV networks. Generally known the results of the measurements of winter and summer on interconnection connecting bus 10(6) kV central power, i.e. the “heads” of feeders known incomplete graphs of currents and voltages, monthly vacation active energy according to an automated system of commercial accounting. Monthly measurements of energy output are made for some transformer substations (TS). Under these conditions, calculations of power losses can be performed using the average load method. The average load on the TS is determined based on the data of monthly measurements of electricity supply on the TS or by dividing the energy measurement on the feeder head in proportion to the power of the TS transformers [1, 5, 8].

Calculation of power losses in the electric network is carried out by the method of average loads. The method of average loads is based on the following relations that allow us to determine the loss of electricity on the resistance $R$ for the period $T$.

\[ \Delta W = 3R \int_0^T I^2(t)dt = 3RM \left[ \frac{I^2}{T} \right]_{T=3R(M/I)}^2 K_T^2 T \]

with a known resistance voltage graph.
\[ \Delta W = \frac{T}{R} \left[ \frac{1}{R} \int_0^T U^2(t) \, dt \right] = \frac{1}{R} [U^2] = \frac{1}{R} (U[V])^2 \cdot K^2_{FU} T, \]

where \( M \) – symbol of the mathematical expectation or average value of the corresponding value for the period \( T \);
\( K^2_{FI}, K^2_{FU} \) – coefficients of the shape of current and voltage graphs.

The main difficulties in the method of average loads consist in determining the integral characteristics of the mode parameters for the period \( T \) (mathematical expectations and form coefficients) for each branch of the scheme, since the information available in the ESO about the mode parameters is very limited.

When calculating the technological power consumption (TPC) in the networks of 6, 10 kV for each feeder are usually known:
- scheme and parameters of the scheme (length and brand of wires of linear sections, brand of transformers of step-down transformer substations (TS));
- daily graphs of current and voltage at the head section of the feeder during the summer and winter control measurements;
- monthly releases of electricity to the feeder from the buses of the feeding substations.

Due to the limited amount of operating information, the energy loss in the feeder is determined in the following sequence: the integral characteristics of the operating parameters of the head branch are determined, the parameters of the equivalent power loss of the feeder replacement circuit are found (Figure 1) and, finally, the equivalent circuit determines the energy loss in the feeder.

![Figure 1. Equivalent feeder replacement scheme [6]](image)

The calculation of energy losses in each feeder is carried out monthly. This makes it more accurate to take into account seasonal unevenness of power consumption and changes in feeder patterns over the course of the year, and this is also necessary for existing reporting in power companies.

The integral characteristics of the mode parameters of the head branch of each feeder for month \( m \) are defined as follows.

The average value of the current head of the branch feeder

\[ I_{avm} = \frac{|W_m|}{24 \sqrt{3} D_m U_{avm} K_{wm}}, \]

where \( W_m \) – energy flow through the head branch of the feeder for a month \( m \);
\( D_m \) – number of days of the month \( m \);
\( U_{avm} \) – mathematical expectation of the bus voltage of the power substation of the month \( m \);
The equivalent circuit of the network section under consideration is compiled and the parameters of the equivalent circuit elements are calculated. Loads in the nodes of the equivalent circuit of the network corresponding to the low voltage buses of transformers TS are determined by the formula:

\[ S_i = S_h \frac{S_{ni}}{S_{n\Xi}}, \]

where \( S_{ni} \) – rated power of the i-th feeder transformer;
\( S_{n\Xi} \) – sum of rated capacities of all feeder transformers;
\( \hat{S}_h = \frac{\hat{W}_h}{T} \) – average for the period \( T \) power of the head branch of the feeder, MVA;

\[ k_c = \frac{W_v}{P_{max} T} = \frac{T_{max}}{T} = \frac{P_{av}}{P_{max}}, \]

where \( k_c \) – graph fill factor is determined by the formula:

\[ k_c = \frac{1 + 2 k_c}{3 k_c}, \]

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There \( W_v \) – electricity supply to the grid during the time \( T \);
\( T_{max} \) – the number of hours that the network's maximum load is used.

In the presence of data on fill factors of the load graph, it is allowed \( k_c = 0.5 \). [3].
\( \dot{W}_h \) – energy passed through the head branch of the feeder for the period \( T \), MG\text{h};  
\( T \) – work period, hours.

The equivalent circuit node corresponding to the tires to which one of the leading branches of the network section is connected is the base node. The voltage in the base node is equal to the average value of the voltage on the busbars of the power center for the \( m \)-th month, determined by (1). The nodes of the equivalent circuit corresponding to the tires, to which other head branches of the network section are connected, are represented in the form of nodes with a given generation [4].

The calculation of current distribution along the branches of the equivalent circuit and voltages in the nodes of the circuit is performed. Then the losses of active and reactive power are determined in all branches corresponding to line sections \( \Delta \dot{S}_{1 \Sigma} \), load losses of active and reactive power corresponding to transformers \( TS \) \( \Delta \dot{S}_{1 \Sigma} \) and idle losses for transformers \( TS \) and idle losses for transformers – \( \Delta \dot{S}_{TS \Sigma} \).

After calculating the steady state at given values \( \dot{S}_i \) the power imbalance in the feeder is checked

\[
\delta \dot{S} = \dot{S}_h - \sum \dot{S}_i - \Delta \dot{S},
\]

where \( \Delta \dot{S} \) – total power loss in the feeder.

If the amount of power unbalance in the feeder is unacceptable, \( |\delta \dot{S}| > \varepsilon_s \) (for example, \( \varepsilon_s = 0.0001 \)), then the loads of the transformers \( TS \) are adjusted

\[
\dot{S}_i := \dot{S}_i + \alpha \cdot \delta \dot{S},
\]

where relaxation coefficient \( \alpha \) is taken equal to 0.5.

The load capacities of \( TS \) transformers are specified until the power unbalance in the feeder becomes acceptable. [7, 9].

3. Results

After the calculation of the feeder operation mode is completed, the total power losses in all linear sections are determined \( \Delta \dot{S}_{1 \Sigma} \), constant \( \Delta \dot{S}_{wp \Sigma} \) and load \( \Delta \dot{S}_{ts \Sigma} \) losses in feeder transformers, on the balance sheet of the network enterprise, as well as the total current \( \dot{I}_r \), passing through the feeder and not entering the transformers on the balance sheet of the network enterprise.

Feeder equivalent circuit parameters \( Z_{tE}, Z_{TE}, Y_{TE}, \dot{\xi} = \dot{I}_h / \dot{I}_a \) are determined based on the calculation of its steady-state operating mode.

\[
\begin{align*}
Z_{te} &= \Delta \dot{S}_{1 \Sigma} / \dot{I}_h^2; \\
\dot{U}_r &= U_h - Z_{te} \cdot \dot{I}_h; \\
Y_{te} &= \Delta \dot{S}_{wp \Sigma} / \dot{I}_r^2; \\
\dot{i}_r &= \dot{i}_h (1 - \dot{\xi}) - Y_{te} \dot{U}_r; \\
Z_{te} &= \Delta \dot{S}_{wp \Sigma} / \dot{I}_r^2; \\
\dot{\xi} &= \dot{I}_h / \dot{I}_a.
\end{align*}
\]

Energy losses in the feeder circuit – in lines \( \Delta \dot{W}_r \), constant \( \Delta \dot{W}_{wp} \) and load \( \Delta \dot{W}_{ts} \) in transformers, according to an equivalent feeder circuit, are defined as follows:

\[
\Delta \dot{W}_r = Z_{te} \cdot M \left[ \dot{I}_r^2 \right] \cdot T;
\]
\[ \Delta \hat{W}_{sp} = Z_{te} \cdot M[I_i^2] \cdot T; \]
\[ \Delta \hat{W}_{sp} = \hat{Y}_{te} \cdot M[U_i^2] \cdot T. \]

Quantities \( \hat{i}_i, \hat{i}_i, \hat{U}_i \) according to the equivalent circuit will be equal to:

\[
\hat{i}_i = \hat{A}_i \hat{U}_h + \hat{C}_i \hat{i}_h, \quad \text{where} \quad \hat{A}_i = 0, \quad \hat{C}_i = 1;
\]

\[
\hat{i}_i = \hat{A}_p \hat{U}_h + \hat{C}_p \hat{i}_h, \quad \text{where} \quad \hat{A}_p = -Y_{te}, \quad \hat{C}_p = 1 - \hat{\xi} + Z_{le} Y_{le};
\]

\[
\hat{U}_i = \hat{A}_p \hat{U}_h + \hat{C}_p \hat{i}_h, \quad \text{where} \quad \hat{A}_p = 1, \quad \hat{C}_p = -Z_{le}.
\]

Mathematical expectations of squared modules of quantities \( \hat{i}_i, \hat{i}_i, \hat{U}_i \) defined by expression

\[ M[V^2] = A_v^2 M[U_h^2] + C_v^2 M[I_h^2] + \frac{2}{T} \text{Re} \left[ \hat{A}_v \hat{C}_v \hat{W}_h \right], \]

where \( V \) – one of the indicated values;

\( \hat{A}_v, \hat{C}_v \) – coefficients of the above expressions.

\( M[I_h^2] \) – determined by average current \( I_{av \ v} \) and the form coefficient \( K_{fI}. \)

\( M[U_h^2] \) – calculated by \( U_{av \ v} \) and the form coefficient \( K_{fU}. \)

We will illustrate the algorithm for calculating the mode using the example of the feeder shown in Figure 2.

\[ \text{Figure 2. Design scheme of the feeder} \]

Power losses in the feeder lines Figure 2 are calculated using the substitution scheme shown in Figure 3.
Figure 3. The equivalent circuit for calculating power losses

The parameters of the elements of the equivalent circuit are calculated by the following formulas. Active, reactive and impedance lines:

\[ r_i = r_0 \cdot \frac{l}{n}, \quad x_i = x_0 \cdot \frac{l}{n}, \quad Z_i = r_i + jx_i, \]

where \( r_0, x_0 \) – linear resistance; 
\( n \) – number of parallel circuits; 
\( l \) – line length [10, 12].

4. Conclusions

The calculation of current distribution in the branches of the equivalent circuit is performed in the following sequence.

1. By measurements released for the estimated interval \( T \) hour of active and reactive energy \( W_a, W_p \) and average voltage \( U_{CP} \) active and reactive components of the head section current are calculated

\[ I_{r,av} = I_{r,av,ac} + jI_{r,av,react}, \]

where

\[ I_{r,av,ac} = \frac{W_a}{\sqrt{3} \cdot U_{CP} \cdot T}, \quad I_{r,av,react} = \frac{-W_p}{\sqrt{3} \cdot U_{CP} \cdot T}. \]

2. The current components of the head section are distributed in proportion to the rated capacities of the transformers connected to the feeder. Nodal currents in the considered circuit Figure 3 will be equal to:

\[ j_2 = \frac{i_{r,av}}{S_{nom,2}} \cdot \frac{S_{nom,2}}{S_{nom,2} + S_{nom,4}}; \quad j_4 = \frac{i_{r,av}}{S_{nom,4}} \cdot \frac{S_{nom,4}}{S_{nom,2} + S_{nom,4}}; \]

where \( S_{nom,2}, S_{nom,4} \) – rated power of transformers in the nodes of the equivalent circuit.
3. The currents in the branches of the substitution scheme are calculated, starting from the branches most distant from the CP:

\[ i_{34} = j_4; \]
\[ i_{35} = j_5; \]
\[ i_{23} = i_{34} + i_{35}; \]
\[ i_{12} = i_{23} + j_2. \]

4. The branch currents found in p. 3 determine the load losses of active power in the lines \( \Delta P_i (i = 1, 2, \ldots, 4) \):

\[ \Delta P_{i1} = 3 \cdot I_{12}^2 \cdot r_{11}; \]
\[ \Delta P_{i2} = 3 \cdot I_{23}^2 \cdot r_{12}; \]
\[ \Delta P_{i3} = 3 \cdot I_{34}^2 \cdot r_{13}; \]
\[ \Delta P_{i4} = 3 \cdot I_{35}^2 \cdot r_{14}; \]

5. Total line losses CH II.

\[ \Delta P_{L_{10}} = \Delta P_{L1} + \Delta P_{L2} + \Delta P_{L3} + \Delta P_{L4}. \]

6. The voltages in the nodes of the network circuit are determined:

\[ \hat{U}_2 = U_{CP} - \sqrt{3} i_{12} Z_{11}; \]
\[ \hat{U}_3 = \hat{U}_2 - \sqrt{3} i_{23} Z_{22}; \]
\[ \hat{U}_4 = \hat{U}_3 - \sqrt{3} i_{34} Z_{33}; \]
\[ \hat{U}_5 = \hat{U}_4 - \sqrt{3} i_{35} Z_{44}. \]

7. Load currents of transformers:

\[ i_{26} = j_2 - i_{x_{rp1}} = j_2 - \left( \frac{\Delta P_{xx2}}{\sqrt{3} U_{nom}} + j \frac{I_{xx2}}{100} \frac{S_{nom2}}{\sqrt{3} U_{nom}} \right), \]
\[ i_{47} = j_4 - i_{x_{rp2}} = j_4 - \left( \frac{\Delta P_{xx4}}{\sqrt{3} U_{nom}} + j \frac{I_{xx4}}{100} \frac{S_{nom4}}{\sqrt{3} U_{nom}} \right). \]

8. Load losses of active power in transformers:

\[ \Delta P_{H_{TP1}} = 3 \Delta P_{xx2} \left( \frac{U_{26}^2 I_{26}^2}{n_y^2 S_{nom2}^2} \right). \]
\[ \Delta P_{H,T\rightarrow 2} = 3\Delta P_{cc,4} \left( \frac{U_4^2 I_{47}^2}{n_{4,4} S_{nom,4}^2} \right), \]

where \( n_{4,2}, n_{4,4} \) - the number of parallel transformers in nodes 2 and 4.

9. Conditionally constant losses of active power in the network transformers are calculated by the formulas:

\[ \Delta P_{x1} = \Delta P_{xx,2} \cdot \left( \frac{U_2}{U_{nom}} \right)^2; \]

\[ \Delta P_{x2} = \Delta P_{xx,4} \left( \frac{U_4}{U_{nom}} \right)^2. \]

Here \( \Delta P_{xx,i}, \Delta P_{cc,i} \ (i = 2, 4) \) – loss of idling and short circuit in the transformer TS [13, 14].

Based on the average load method, SET10 and GORSET programs were developed for calculating the technical losses of electricity in 10 (6) kV networks.

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