Reduction of electrical energy losses of power transformers of 25 kV traction substations

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Abstract. The aim of the study is to reduce the losses of electrical energy in power transformers of AC traction substations. To reduce the losses of electrical energy, interval counterregulation of performance indicators in the traction power supply system is performed. The planning of the electrical energy losses is determined by the predictive time intervals. The electrical energy losses in the time interval are determined by the power losses of instantaneous circuits. Instantaneous circuits determine the voltage of the windings of transformers, the currents of the power supply arms of the electric traction network, the transformation ratios, the temperature of the windings and the power of regional loads. The predictive values of the instantaneous circuits are determined by the results of the monitoring of the completed train schedules, statistical analysis and simulation modeling of the operation of the traction substation. The initial data for the calculation are the predictive discrete values of the performance indicators of the traction power supply system. The calculation of power losses in steel in power transformers is performed taking into account voltage unbalance. Copper losses are determined in phases, taking into account the distribution of arm currents in the windings and the actual transformation ratios. Actual transformation ratios are determined based on the voltage control stage. The effect of winding temperature on power losses is taken into account by the temperature coefficient of resistance. The number of transformers in operation at the predictive time intervals is selected by the minimum loss of electrical energy. The accuracy of the choice of the number of transformers in operation is checked by analyzing the implementation of the forecast train schedule. The error of the initial data and simulation modeling is determined by comparing the predictive values and the monitoring results. It is proposed to carry out performance management of the traction power supply system on the basis of digital technologies.

1. Introduction
The strategy of the scientific and technical development of the Russian Railways holding for the period up to 2020 envisages an increase in the energy efficiency of the transportation process. One of the target areas is the reduction of electricity consumption for train traction. In order to improve the efficiency of the organization of transportation activities, it is necessary to move from reactive control to modeling and forecasting the development of situations [1].

It has been proposed to reduce the electrical energy loss in the traction power supply system (TPSS) by selecting the normal power supply circuits for traction loads [2]. The algorithm of choosing the number of power transformers of traction substations (traction transformers) in operation for the minimum losses is considered in [3]. The accuracy of the selected power supply circuits for traction loads is determined by matching the calculated and actual losses. This being the case, electric energy losses are determined for predictive and completed train schedules [4].
2. Problem definition

The currents of the windings of the traction transformers are determined by the currents of the arms and the power of the regional consumers. The currents of the arms are related to an interval train schedule. With that, the planned train schedule can be timely adjusted by the train dispatcher. The static display of the dynamic process of the TPSS operation at a single point in time, characterized by discrete values of the performance indicators, is called an instantaneous circuit. The monitoring system allows one to record discrete values of indicators of the TPSS performance in the form of instantaneous circuits in the database. The results obtained on the basis of DBMS and simulation modeling [5, 6] make it possible to determine the predictive integral indicators of TPSS. Power supply schemes of traction loads are determined at intervals of time [7]. It has been proposed to reduce the loss of electrical energy in the TPSS, taking into account losses in traction transformers. The number of transformers in operation is determined by [8] with interval counterregulation of performance indicators.

The extendability of the service life due to thermal wear of the insulation of the windings of traction transformers was proved in [9]. The uneven wear of the insulation occurs due to asymmetrical currents of the transformer windings. New circuits for connecting the transformer bushings to electric transmission lines and electric traction network reduce the intensity of winding wear with minimal residual life. Therefore, the calculation of power losses and electrical energy is relevant when determining the residual insulation life of the windings of the traction transformers [10, 11, 12].

As a rule, two traction transformers are used at AC traction substations. To supply traction loads, traction transformers are installed, for example, of a type TDTNZH 40000 / 220-76 U1 with a rated power of 40 MVA and a winding connection circuit $Y_0/\Delta / \Delta-11-11$. Three-phase transformers of 220 and 110 kV voltage classes are equipped with a on-load tap changer (LTC) at the zero point of the upper voltage windings. One stage of regulation by an on-load tap changer for a traction transformer with a voltage class of 220 kV is 1% at ± 12 steps, for a voltage class of 110 kV - 1.78% at ± 9 steps, respectively. Nominal no-load losses $(\Delta P_{n})$ are 51 kW. Short circuit losses $(\Delta P)$ of 230 kV and 27.5 kV windings are 192 kW, of 230 kV and 11 kV windings are 208 kW, of 25 kV and 11 kV windings are 165 kW.

Power losses at n traction transformers of the same type $(\Delta P_n)$ are usually determined by the formula [13]:

$$\Delta P_n = n\Delta P_{nx} + \frac{\Delta P_k}{nS_{wind}^2} \times S_{load}^2,$$

(1)

where $\Delta P_{nx}$ are the no-load losses of the power transformer, kW; $\Delta P_k$ are short circuit losses, kW; $S_{wind}$ is the rated power of the traction transformer, kVA; $S_{load}$ is the transformer load power, kVA.

Formula (1) does not take into account the asymmetry of currents and voltages, the temperature of the windings and the actual transformation ratios.

Electricity losses in the steel of a power transformer with a symmetrical voltage of the windings have been proposed [14] to be determined by the formula:

$$\Delta W_k = \Delta P_{nx} \sum_{j=1}^{k} T_{pj} \left( \frac{U_j}{U_{wind}} \right)^2,$$

(2)

where $T_{pj}$ is the operating time of the transformer at the jth actual voltage, h; $k$ is the number of values of the actual voltage; $U_j$ is the winding voltage at the j-th voltage value, kV; $U_{wind}$ is the nominal voltage of the transformer winding, kV.

The special features of TPSS include a single-phase traction load. As a result, the voltages and currents of the windings of the upper, traction and regional voltage of the traction transformers of the substations are asymmetrical. Formula (2) does not take into account voltage asymmetry [15]. Determining the loss of electrical energy in steel by formulas (1) and (2) does not yield an accurate result.

3. Materials and methods

We consider the loss of electrical energy of the traction transformers at actual voltages and winding currents. Asymmetric system of voltage vectors of windings AX, BY and CZ (Figure 1.) will be obtained...
as the sum of symmetric systems of voltages of direct (U_{1i}) and reverse (U_{2i}) sequence [16]. Figure 1 shows the currents of the upper voltage windings (I_{AX}, I_{BY}, I_{CZ}) of the traction voltage (I_{ax}, I_{by}, I_{cz}) and currents of regional windings (I_{pax}, I_{pby}, I_{pcz}). The currents of the left and right power supply arms (I_{L}, I_{R}) are oriented with respect to the voltage of the arms (U_{L}, U_{R}). The operators of the voltage rotation of the arms (D_{L}, D_{R}) take into account the voltage vector in phase coordinates.

\[ \Delta P_{sti} = \Delta P_{st1i} + \Delta P_{st2i}. \]  

(3)

where \( i \) is the sequence number of the instantaneous circuit.

Power losses in steel from the voltage of direct sequence are determined by the formula:

\[ \Delta P_{st1i} = \Delta P_{xx} \left( \frac{U_{1i}}{U_{nom}} \right)^2. \]  

(4)

where \( U_{nom} \) is the nominal voltage of the transformer winding, kV; \( \Delta P_{xx} \) are no-load losses of the traction transformer, kW.

Power losses in steel from the voltage of reverse sequence are determined by the formula:

\[ \Delta P_{st2i} = \Delta P_{xx} \left( \frac{U_{2i}}{U_{nom}} \right)^2. \]  

(5)

Let us determine power loss in copper in traction transformers by the amount of losses on the active resistances of the windings of the upper, traction and regional voltage for each phase by the currents of the power supply arms of traction loads and power of regional loads:

\[ \Delta P_{ci} = \Delta P_{ui} + \Delta P_{pi} + \Delta P_{ri}. \]  

(6)

The load power losses in the windings of the upper voltage (\( \Delta P_{ui} \)) are determined by the formula:

\[ \Delta P_{ui} = (I_{AX}^2 + I_{BY}^2 + I_{CZ}^2) \cdot R_{ui} \cdot 10^{-3}. \]  

(7)

where \( I_{AX}, I_{BY}, I_{CZ} \) is the module of currents of windings of the upper voltage AX, BY and CZ, respectively; \( A; R_{ui} \) is the active resistance of the windings of the upper voltage, taking into account the temperature of the windings and the on-load tap-changing step, Ohm.
The effective active resistance of the winding of the upper voltage traction transformer, taking into account the temperature and the on-load tap-changing step [17], is:

\[ R_{U1} = (R_{U20} + \Delta R_{U20})[1 + \alpha(t_{windi} - 20)] , \]  
where \( R_{U20} \) is the nominal active resistance of the upper voltage windings, Ohm; \( \Delta R_{U20} \) is the increment of the resistance of the upper voltage winding, taking into account the on-load tap-changing step; \( \alpha \) is the temperature coefficient of resistance; \( t_{windi} \) is the temperature of the windings, °C.

The modules of currents of the windings AX, BY and CZ of the transformer’s upper voltage are determined by the formulas:

\[ I_{AXi} = \left| \frac{1}{n_{Ti}} I_{axi} + \frac{1}{n_{Ri}} D_{AXi} I_{Ri} \right| \]
\[ I_{BYi} = \left| \frac{1}{n_{Ti}} I_{byi} + \frac{1}{n_{Ri}} D_{BYi} I_{Ri} \right| \]
\[ I_{CZi} = \left| \frac{1}{n_{Ti}} I_{czi} + \frac{1}{n_{Ri}} D_{CZi} I_{Ri} \right| \]  

where \( I_{axi}, I_{byi}, I_{czi} \) are the currents of the traction windings; \( D_{AX}, D_{BY}, D_{CZ} \) are the operators of the voltage rotation of the windings \( ax, by, cz \) of regional loads’ currents, respectively; \( I_{Ri} \) is the current of the regional load; \( n_{Ti}, n_{Ri} \) are the actual transformation ratios of the windings of the upper and traction voltage, of the upper and regional voltage, respectively.

Actual transformation ratios can be determined by formulas (10) and (11), taking into account the nominal winding ratio of the upper and traction voltage \( (n_{Tnom}) \), the windings of the upper and regional voltage \( (n_{Pnom}) \) and the on-load tap-changing step \( (\Delta n_{Ti}, \Delta n_{Ri}) \):

\[ n_{Ti} = n_{Tnom} + \Delta n_{Ti} , \]
\[ n_{Ri} = n_{Rnom} + \Delta n_{Ri} . \]

The currents of the traction windings \( ax, by, cz \) we determine through the currents of the arms and the operators of the voltage rotation of the power supply arms:

\[ I_{axi} = a_{Rax} D_{Ri} I_{Ri} - a_{Lax} D_{L} I_{Li} \]
\[ I_{byi} = \frac{1}{3} D_{Ri} I_{Ri} - \frac{1}{3} D_{L} I_{Li} \]
\[ I_{czi} = a_{Rcz} D_{Ri} I_{Ri} - a_{Lcz} D_{L} I_{Li} \]  

where \( I_{axi}, I_{byi}, I_{czi} \) are the currents of the left and right power supply arms, respectively; \( A, D_{L}, D_{R} \) are the operators of voltage rotation of the left and right power supply arms in phase coordinates; \( a_{Rax}, a_{Lax}, a_{Rcz}, a_{Lcz} \) are the distribution coefficients of currents of arms in the transformer windings.

The current of the regional load will be determined by the formula:

\[ I_{Ri} = \sqrt{\frac{P_{Ri}^2 + Q_{Ri}^2}{k_{cx} k_{cy} U_{Ri}^2}} e^{j(\arctg \frac{Q_{Ri}}{P_{Ri}})} , \]

where \( P_{Ri}, Q_{Ri} \) is the active and reactive power of the regional load, kW and kVAR; \( U_{Ri} \) is the regional load voltage, kV; \( k_{cx} = 3 \) with the circuit of connecting the regional voltage windings into a “triangle”; \( k_{cy} = \sqrt{3} \) with the circuit of connecting the regional voltage windings into a “star”.

Power losses in the windings of the traction voltage \( (\Delta P_{Ti}) \) we define by the formula:

\[ \Delta P_{Ti} = (I_{axi}^2 + I_{byi}^2 + I_{czi}^2) \cdot R_{Ti} \cdot 10^{-3} , \]
where \( I_{axi}, I_{byi}, I_{czi} \) are the modules of currents of the transformer traction windings, A; \( R_{Ti} \) is the active resistance of traction voltage windings taking into account the temperature of the windings, Ω.

The effective resistance of the traction winding, taking into account the temperature, is calculated by the formula:

\[ R_{Ti} = R_{T20} [1 + \alpha(t_{windi} - 20)] , \]
where \( R_{T20} \) is the nominal active resistance of the traction voltage windings, Ohm.

Power losses in the windings of the regional voltage \( (\Delta P_{Pi}) \) we define by the formula:

\[ P_{Pi} = 3I_{Ri}^2 R_{Pi} \cdot 10^{-3} , \]
where \( R_{Pi} \) is the effective resistance of the regional winding, taking into account the temperature and the step of the on-load tap-changer and off-load tap changer, Ohm, which we calculate by the formula:

\[
R_{Pi} = (R_{R20} + \Delta R_{R20})[1 + \alpha(t_{windi} - 20)].
\]

where \( R_{R20} \) is the nominal active resistance of the windings of the regional load, Ohm; \( \Delta R_{R20} \) is the increment of the regional winding resistance, taking into account the voltage tapping step.

4. Results

We determine the total power losses with one traction transformer in operation by the formula:

\[
P_{1i} = \Delta P_{STi} + \Delta P_{Uli} + \Delta P_{Ti} + \Delta P_{Ri}. \tag{18}
\]

Power losses with two traction transformers in operation are respectively equal to:

\[
\Delta P_{2i} = 2\Delta P_{STi} + \frac{1}{2}(\Delta P_{Uli} + \Delta P_{Ti} + \Delta P_{Ri}). \tag{19}
\]

Thus, the losses of electrical energy for the billing period, when \( n \) traction transformers in operation, are determined by the formula:

\[
\Delta W_{ni} = (\sum_{i=1}^{m} \Delta P_{ni})\Delta t, \tag{20}
\]

where \( \Delta t \) is the instantaneous circuit time; \( m \) is the number of instantaneous circuits in the time interval.

Reducing the electric power losses of the traction transformers is performed by selecting their number in operation for the predictive time intervals. The electrical energy losses for the billing period are determined by the time intervals, taking into account the efficient use of the resource of switching devices.

5. Conclusion

1. It is proposed to increase the efficiency of TPSS operation by choosing the number of traction transformers in operation based on digital technologies.
2. The article proposes formulas for calculating power and electrical energy losses in traction transformers with asymmetric voltages and winding currents, taking into account the winding temperature and actual transformation ratios.

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