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Energy efficiency of heat tests for traction electric machines

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Abstract. The article discusses one of the options to reduce the electricity consumption for the carry out acceptance of post-repair tests of traction electric machines. Heating tests of traction electric machines at the mutual load stand are the most energy-intensive part of the entire test program. Energy consumption for this type of test can be reduced, for this, an analysis of thermal processes in the windings of traction electric machines during their heating test was given. The energy efficiency coefficient of the mutual load system is formulated. The energy efficiency coefficient for the traction electric machine NB-406 is calculated. The calculation results showed that with an increase in the test current by 30%, the total losses in the motor windings decrease by about one and a half times, while the test time decreases by almost three times. An increase in test current and a decrease in test time do not reduce the quality of the test, and the results obtained. A methodology for assessing the energy efficiency of heating tests is proposed. It can be applied at test sites of depots, as well as repair plants. This will reduce the material costs of testing, without compromising the quality of the tests themselves.

1. Introduction

The reduction of energy consumption for acceptance tests after the repair of traction electric machines is one of the urgent problems at the repair plants of traction rolling stock. The most energy-intensive part of the entire test program of traction electric machines at a back-to-back stand are heat tests. Performing this kind of test, energy consumption can be reduced both by increasing the energy efficiency of the loading back test, and by optimizing the loading mode of traction electric machines.

2. Research problem statement

In accordance with IEC 60349-1: 2010, NEQ [1], traction electric machines are tested during acceptance tests for one hour at a rated voltage and current giving a temperature rise corresponding to a temperature rise in nominal mode. In fact, this current value corresponds to the one-hour mode.

Obviously, part of the thermal energy released in the windings of the tested electric machine is emitted into the environment and does not participate in the formation of the thermal potential of the windings, during the time of the heating test [2, 3]. The goal of these tests is to heat the windings of the traction electric machine to a certain temperature rise in certain time at a given heat transfer power. From this point of view, that part of the thermal energy released in the windings that is used to increase their temperature is useful. It is determined by the equivalent heat capacity and the specified temperature rise, and does not depend on the test mode. Therefore, a reduction in the energy consumption for thermal tests can be achieved by minimizing the total heat transfer energy during heating to a predetermined temperature rise [4-6].

A preliminary qualitative analysis of the thermal processes occurring during these tests shows that the heat transfer energy during heating to a predetermined temperature rise of the windings of the electric machine decreases with increasing current. An increase in current leads to a decrease in heating time as well. Therefore, the ceteris paribus, the greater the load current value of the tested electric machine, the less the energy consumption for its heating.

Let's take a closer look at the thermal processes when heating the armature windings of a traction electric machine during its test with a constant current load for a more accurate quantitative assessment of the influence of the test value of current on the power consumption. Anchor winding is a heating limit [7] for most traction electric motors of electric rolling stock.

3. Determination of the energy efficiency of heating the armature winding

The differential equation for heating the armature winding is [8]:

$$\Delta P_{rd}\mathrm{d}t = C_{rd}\mathrm{d}\tau + B_{rd}\tau \cdot \mathrm{d}t\,, \tag{1}$$

where ΔP_{rd} – reduced power loss;

C_{rd} – reduced heat capacity;

B_{rd} – reduced heat transfer;

τ – temperature rise;

t – time.

Dividing the left and right sides of expression (1) by $\mathrm{d}t$, we obtain the power balance equation:

$$\Delta P_{rd} = C_{rd}\frac{\mathrm{d}\tau}{\mathrm{d}t} + B_{rd}\tau\,. \tag{2}$$

Let us introduce the notation for the terms on the right side of the equation (2):

$$P_c = C_{rd}\frac{\mathrm{d}\tau}{\mathrm{d}t}, \tag{3}$$

$$P_в = B_{rd}\tau\,, \tag{4}$$

where P_c – power losses for heating the windings of an electric machine;

P_e – heat transfer power loss.

Then equation (2) takes the form:

$$\Delta P_{rd} = P_c + P_в\,. \tag{5}$$

Integrating the right and left sides of the expression (1) we obtain the equation of thermal energy balance:

$$\int_0^{t_1}\Delta P_{rd}\mathrm{d}t = C_{rd}\tau_1 + \int_0^{t_1}B_{rd}\tau\mathrm{d}t\,, \tag{6}$$

where t_1 – test time;

τ_1 – temperature rise at time t_1.

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Definite integral $\int_0^{t_1} \Delta P_{rd} \mathrm{d}t$ represents the total thermal energy released in the armature winding. At time t_1, one part of this energy, equal to $C_{rd}\tau_1$, was spent on raising the temperature of the winding, and the other, equal to $B_{rd}\int_0^{t_1} \tau \mathrm{d}t$, was scattered into the environment.

Reduced power loss ΔP_{rd} can be represented as [8]:

$$\Delta P_{rd} = I^2 R_0 + I^2 R_0 \alpha\tau + k_c \Delta P_c, \quad (7)$$

where R_0 – armature winding resistance at ambient temperature;

α – temperature coefficient of resistance;

k_c – coefficient taking into account the influence of iron loss on heating of the armature winding;

ΔP_c – iron loss.

In general, the losses ΔP_{rd} can be represented as:

$$\Delta P_{rd} = \Delta P_e + \Delta P_\tau, \quad (8)$$

where $\Delta P_e = I^2 R_0 + k_c \Delta P_c$ – equivalent losses provided $\tau = 0$;

$\Delta P_\tau = I^2 R_0 \alpha\tau$ – additional temperature rise-dependent losses.

To keep it simple, let's introduce the following notation for the terms of the equation (6) the balance of thermal energy:

$$Q_p = \int_0^{t_1} \Delta P_{rd} \mathrm{d}t; \quad (9)$$

$$Q_c = C_{rd}\tau_1; \quad (10)$$

$$Q_в = B_{rd}\int_0^{t_1} \tau \mathrm{d}t. \quad (11)$$

where Q_p – energy expended in testing;

Q_c – energy spent on heating the motor windings;

$Q_в$ – energy dissipated in the environment.

Then equation (1) takes the form:

$$Q_p = Q_c + Q_в, \quad (12)$$

$$k_{ef} = \frac{Q_c}{Q_p} = \frac{Q_c}{Q_c + Q_в}, \quad (13)$$

where k_{ef} – coefficient of energy efficiency.

The purpose of thermal tests is to heat the armature winding at a given current I and heat transfer B_{rd} to temperature rise τ_1 during time t_1, then the energy Q_c is useful, that is, spent only on increasing τ. The ratio of this energy to total energy Q_p will characterize the energy efficiency of the heating test.

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The coefficient of energy efficiency will shows how much of the thermal energy released in the armature winding is spent on raising its temperature.

To maximize k_{ef} provided $Q_c = \text{const}$, compliance with condition $Q_в \to \min$ is necessary.

Figure 1 shows the temperature rise τ and power ΔP_{rd}, P_c, $P_в$ included in equation (5) curves × time t.

The area of the figure ABE0 represents the total thermal energy Q_p for time t_1. The area of the figure 0CE is the energy $Q_в$, which is scattered into the environment. The area of the figure ADE0 represents the energy Q_c, which is spent on heating until the temperature rises τ_1.

A preliminary analysis of the curves in Figure 1 shows that with an increase in the heating rate $\frac{\mathrm{d}\tau}{\mathrm{d}t}$ at a fixed value of τ_1, the energy $Q_в$ will decrease. Therefore, with increasing current I, the coefficient k_{ef} will increase.

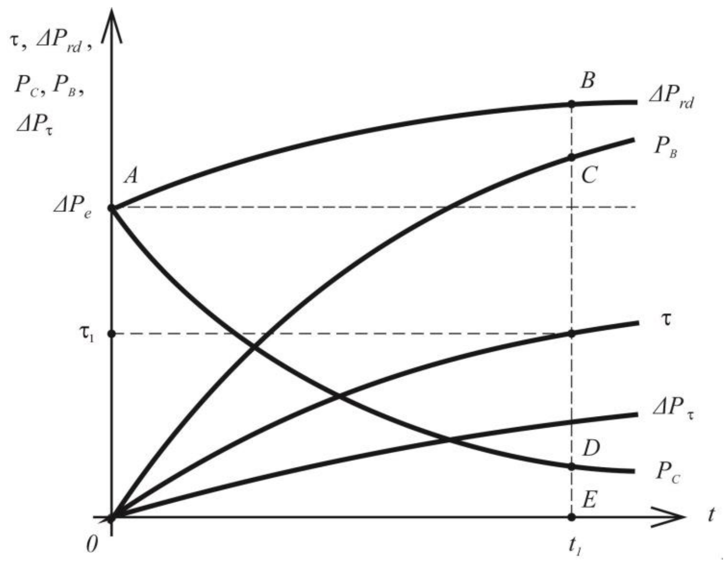

Figure 1. Curves of changes in motor parameters during tests.

Let's find the dependence $k_{ef} = f(I)$ in an analytical form according to formula (6) for the possibility of a quantitative analysis of the effect of the current value I on energy consumption during the test.

The dependence of the temperature rise τ on time t can be represented in the form [8]:

$$\tau = \tau_\infty \left(1 - e^{-\frac{t}{T_e}}\right), \tag{14}$$

where τ_∞ – steady-state temperature rise;

T_e – equivalent heating time constant.

The steady-state temperature rise and the equivalent heating time constant can be calculated by the formulas [4]:

$$\tau_\infty = \frac{\Delta P_e}{B_{rd} - I^2 R_0 \alpha}, \tag{15}$$

$$T_e = \frac{C_{rd}}{B_{rd} - I^2 R_0 \alpha}. \tag{16}$$

With a known value of τ_1, the test time t_1 can be found from equation (14) in the form:

$$t_1 = T_e \cdot \ln \frac{\tau_\infty}{\tau_\infty - \tau_1}. \tag{17}$$

Substituting expressions (14) into equation (11), we obtain:

$$Q_в = B_{rd} \int_0^{t_1} \tau \mathrm{d}t = B_{rd} \int_0^{t_1} \tau_\infty \left(1 - e^{-\frac{t}{T_e}}\right) \mathrm{d}t = B_{rd} \left(\tau_\infty \cdot t_1 - \tau_1 \cdot T_e\right). \tag{18}$$

Substituting expressions (9-11) and (18) for Q_c and $Q_в$ into equation (13), after the transformations, we obtain:

$$k_{ef} = \frac{\tau_1}{\tau_1 + \left(\tau_\infty \cdot t_1 - \tau_1 \cdot T_e\right) \cdot \dfrac{B_{rd}}{C_{rd}}}. \tag{19}$$

The ratio B_{rd}/C_{rd} will be found from equation (16):

$$\frac{B_{rd}}{C_{rd}} = \frac{1}{T_e} + \frac{\alpha \Delta P_e}{C_{rd}}. \tag{20}$$

The ratio $\Delta P_e / C_{rd}$ can be found from an analysis of equation (2) of the power balance at time $t = 0$. For this point in time, the expressions:

$$\Delta P_{rd} = \Delta P_e, \tag{21}$$

$$B_{rd} \cdot \tau = 0. \tag{22}$$

The expression (2) can be written as equation:

$$\Delta P_{rd} = C_{rd} \left. \frac{\mathrm{d}\tau}{\mathrm{d}t} \right|_{t=0}. \tag{23}$$

The derivative $\frac{\mathrm{d}\tau}{\mathrm{d}t}$ at time $t = 0$ can be found from expression (14) as equation:

$$\left. \frac{\mathrm{d}\tau}{\mathrm{d}t} \right|_{t=0} = \frac{\tau_\infty}{T_e}. \tag{24}$$

Substituting expressions (24) into equation (23) for ΔP_e, we obtain:

$$\Delta P_e = \frac{C_{rd} \tau_\infty}{T_e}. \tag{25}$$

Therefore, the ratio $\Delta P_e / C_{rd}$ can be found in the form equation:

$$\frac{\Delta P_e}{C_{rd}} = \frac{\tau_\infty}{T_e}. \tag{26}$$

After appropriate transformations, expression (20) can be written as equation:

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$$\frac{B_{rd}}{C_{rd}} = \frac{1+\tau_\infty \alpha}{T_e}. \tag{27}$$

By substituting (27) into expression (19) after transformations, we obtain:

$$k_{ef} = \frac{T_e \cdot \tau_1}{\tau_\infty \left(t_1 + \alpha\left(\tau_\infty t_1 - \tau_1 T_e\right)\right)}. \tag{28}$$

The reciprocal of k_{ef} is the ratio as equation:

$$\frac{1}{k_{ef}} = \frac{Q_p}{Q_c}. \tag{29}$$

Which shows how many times the total energy of losses in the armature of the traction motor when testing it is more than the energy spent on heating the armature winding.

Table 1 shows the results of calculating the dependencies $t_1 = f(I)$, $k_{ef} = f(I)$, and $1/k_{ef} = f(I)$ obtained for the traction motor NB-406 using the thermal characteristics of its armature winding $(\tau_1 = 120°C)$ [7].

Table 1. Results of calculating the dependencies $t_1 = f(I)$, $k_{ef} = f(I)$, and $1/k_{ef} = f(I)$.

I, A	t_1, min	k_{ef}	$1/k_{ef}$
380	56.5	0.43	2.32
440	28.9	0.57	1.75
485	20.4	0.63	1.59
530	14.9	0.67	1.5
600	10.4	0.7	1.42

Graphs of functions $t_1 = f(I)$ and $k_{ef} = f(I)$ are presented in Figure 2. It can be seen from the graphs in Figure 2 that with an increase in the test load current of the traction motor, the energy efficiency of the heating tests increases, and the test time decreases significantly.

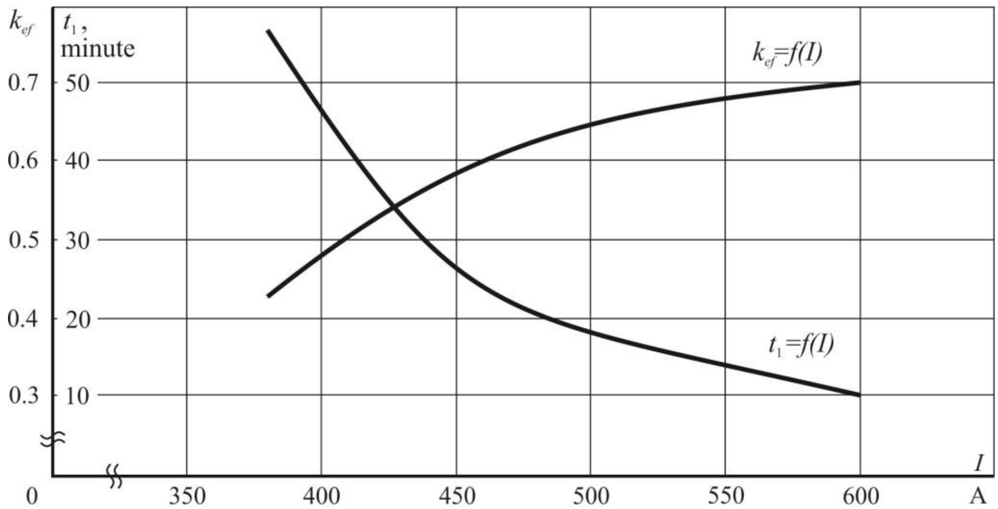

Figure 2. Graphs of functions $t_1 = f(I)$ and $k_{ef} = f(I)$.

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4. Conclusions

Table 1 shows that during heating tests of the NB-406 traction motor with a load current close to the starting value (485 A), the total energy loss in the armature is almost one and a half times lower than in the one-hour mode (380 A). At the same time, the time of thermal testing is reduced by almost three times. It should be noted that the electric losses in other windings of the tested electric machine with an increase in the test current value decrease no less than the losses in the limiting winding (armature winding). These conclusions will be true for other types of traction electric machines of traction rolling stock.

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