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Correction of ted field weakening switching diagram for mainline diesel locomotives of te type

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Abstract. The processes are considered when the stages of weakening of the TED magnetic field are switched on on diesel locomotives of the TE10 type. The analysis of the unstable operation and automatic switching on of the transition relay at partial loads corresponding to the locomotive's speed at the rated load in operation is carried out. TED current algorithms are proposed for correcting the scheme for switching on the relay of transitions from a full field to a weakened field. A variant of the correction circuit is proposed to check its operation during operation. This principle has been violated since the creation of the TE10 diesel locomotive. It is still violated on TE10 diesel locomotives, except for diesel locomotives equipped with the USTA system.

1 Introduction

During the commissioning of diesel locomotives with a capacity of 2000 kW, there were many claims from the operation for the unstable operation of the TED excitation attenuation relay that controlled the activation of the contactors VSH1 and VSH2 for excitation of traction motors (TED).

The main one was the inconsistency of direct switching from the full field (FS) to the weakened field of the first stage (OP1) and from the weakened field OP1 to the weakened field of the second stage (OP2), tuned in rheostat tests at the maximum load of the DGU, at partial loads, i.e., e. lower positions of the regulator [1-3].

For a long time, many researchers and organizations have been developing such developments as systems with non-contact relays, a system with speed control from sensors installed on the wheelset axle, the circuit for switching on the current coils of the relay transitions to the driving winding of the amplifier and the output of the node for extracting the maximum signal from the current transformers; the inclusion of current coils of relay transitions in the amplistat control winding has been changed [4-5]. But all efforts did not reach the main goal - automatic switching on of transient relays at partial loads, corresponding to the locomotive's speed at rated load. The exception was a system using non-contact transfer relays, but it was not accepted because of the complexity because it was included in the selective node [6]. Therefore, based on the study of the experience of

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previous developments, the tasks were set to find a solution that would eliminate this problem.

Disadvantage - the lower the load of the DGU, the faster the direct switching of the FS AF1 and AF1 AF2 [7-9].

An analysis of the operation of diesel locomotives 2TEI16 and type TE10 over many years has shown that the stage switching system is often unstable [10-11]. The main reason is the converging (non-parallel) lines of the switching diagram, which, in turn, are due to the converging lines of switching on and off the transition relay RD-3010.

The unstable operation of the switching system has been noted in numerous publications for many years [12–14].

The unstable factor of the switching diagram is:

- untimely switching on and off, inconsistent with the calculated points of the locomotive traction characteristic, traction force - speed;
- lack of inclusion or deactivation;
- burning of power contacts of contactors of weakening of excitation;
- "ringing work" RPI and RP2.

The switching diagram reflects the complexity of a diesel locomotive's dynamic electric transmission system with an essentially non-linear (relay) characteristic. The term "ringing work" means "self-oscillations" in the control system.

Previously [3], attention was drawn to the systematic tendency of the switching control system to self-oscillations and misalignments, i.e., untimely switching of relays RPI and RP2. Then statistical materials were collected on failures of the switching system [5].

The converging characteristics of the differential relay transition lead to the switching being carried out according to the principle: the smaller the position of the controller, there, at higher the speed, and direct switching occurs, which contradicts the conditions for implementing traction [5].

Direct switching is set during rheostat tests at the 15th position of the controller at currents:

- FS→AFI - 3I00 A;
- AFI→AF2 - 2900 A.

Therefore, the switching lines AFI→AF2 at controller positions below 9÷10 fall into the voltage limitation zone. The voltage does not increase, the power drops, the train does not accelerate, and the switching AFI → AF2 does not occur.

Adjustment to lower currents is not performed due to the possibility of self-oscillations of the automatic control system ("ringing operation").

The analysis aims to find TED's current algorithms for correcting the switching diagram PP⇄OP1.

The following assumptions were made in the analysis:

- real TED are replaced by conditional ones [4]. This excludes the influence of other TEDs on the transition process;
- PC train contactors are on during the entire transient process (we exclude them from the scheme);
- All TEMs have the same electromechanical characteristics and winding parameters;
- magnetization curves of the traction generator and TED are approximated by two straight line segments [5];
- the degree of weakening of the TED magnetic flux is the same;
- pre-transition mode of locomotive operation at $t = 0^{+}$stationary;
- the coefficient of dispersion of the magnetic flux remains constant [5].

2 Methods

Consider the equivalent circuit of the power circuit of a diesel locomotive when switching FS⇄AF1. Considering the accepted assumptions, the equivalent circuit of the studied transient processes is shown in Fig. 1.

Conditional TED winding parameters:

$$R_{du} = \frac{R_r}{n};\ L_{du} = \frac{L_r}{n},$$

where: n is the number of parallel branches of TED; R_r, L_r are resistance and inductance of the corresponding winding of a real TED.

In the following, the indices "u" and "r" are omitted

Drawing up equations and their solution when switching FS → AF1

Following the equations and their solutions, the equations of the studied transient process are compiled.

$$L_g \frac{di_1}{dt} + R_g i_1 + L_{du} \frac{di_1}{dt} + R_{du} i_1 + R_{sh} i_3 = U_g - \mathrm{K}_d i_2 + K_{shg} i_1 - K_{shd} i_1;$$

$$L_{obd} \frac{di_2}{dt} + R_{obd} i_2 - R_{sh} i_3 = 0; \qquad (1)$$

$$i_1 - i_2 - i_3 = 0,$$

where: i_1 is armature current and additional pole (DP) of TED; i_2 is current of the excitation winding (OV) of the TED; i_3 is current of the resistor of the shunting OB TED; L_{du} is armature inductance and DP TED; L_{obd} is OV TED inductance; L_g is the inductance of the armature and DP of the traction generator; R_{du} is resistance of the armature circuit and DP TED; R_g is resistance of the traction generator armature circuit; R_{sh} is resistance of the resistor shunting the OB TED; $K_d = \frac{\Delta E_d}{\Delta i_l}$ is TED transfer coefficient; ΔE_d is increment of the counter emf of TED; K_{shd} ,K_{shg} are transfer coefficients of reaction of the TED armature and traction generator.

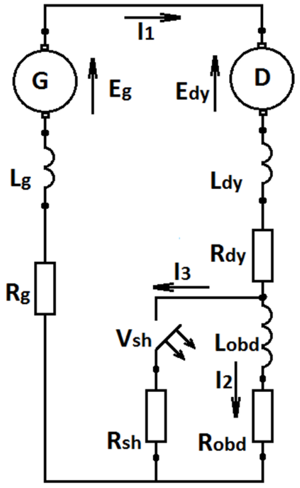

Fig. 1. Equivalent circuit of the power circuit of a diesel locomotive of the TE10 type when switching the FS to AF1 and AF2

Image of the system of equations according to Laplace:

$$P(L_{du}+L_g)I_1(P)+(R_g+R_{du})I_1(P)+(K_{shg}-K_{shd})I_1(P)+$$
$$+K_d I_2(P)+R_{sh}I_3(P)=\frac{U_g}{P}+L_{du}i_1(0)+L_1 i_1(0); \tag{2}$$
$$PL_{obd}I_2(P)+R_{obd}I_2(P)-R_{sh}I_3(P)=L_{obd}i_2(0);$$
$$I_1(P)-I_2(P)-I_3(P)=0,$$

where $P=\frac{d}{dt}$

Determinant of the characteristic function of the system (2)

$$D(p)=\begin{vmatrix} P(L_g+L_{du})+(R_g+R_{du})+(K_{shg}-K_{shd}); & K_d; & R_{sh} \\ 0; & PL_{obd}+R_{obd}; & -R_{sh} \\ 1 & -1 & -1 \end{vmatrix} \tag{3}$$

Expanding the determinant D(p) and equating it to zero, we obtain the characteristic equation:

$$\mathrm{A}Ap^2+Bp+C=0 \tag{4}$$

where $A=L_{obd}(L_{du}+L_g)$;

$$B=L_{obd}(R_g+R_{du}+R_{sh})+(K_{shg}-K_{shd})+(L_g+L_{du})(R_{obd}+R_{sh});$$
$$C=(R_g+R_{du}+K_{shg}-K_{shd})(R_{obd}+R_{sh})+R_{sh}(K_d-R_{obd}).$$

Denote

$$\frac{B}{A}=2a; \quad \frac{C}{A}={\omega_0}^2. \tag{5}$$

Then the characteristic equation will take the form:

$$p^2+2ap+{\omega_0}^2=0. \tag{6}$$

The values $\mathcal{L}_1,\mathcal{L}_2$are the roots of the characteristic equation

$$\mathcal{L}_1,\mathcal{L}_2=p_1,p_2=-a\pm\sqrt{a^2-{\omega_0}^2} \tag{7}$$

will be determined by the values of the coefficients B and C. Since the value of the coefficient A cannot take negative values during the entire transient process.
Compose and calculate the determinant D_I (P):

$$D_1(\mathrm{P})=\begin{vmatrix} \frac{U_g}{P}+L_g i_1(0)+L_{du}i_1(0) & K_d & R_{sh} \\ L_{obd}i_2(0) & PL_{obd}+R_{obd} & -R_{sh} \\ 0 & -1 & -1 \end{vmatrix} \tag{8}$$

Its calculation gives:

$$D_1(\mathrm{P})=-\left[\frac{U_g}{P}+(L_g+L_{du})i_1(0)\right](PL_{obd}+R_{obd})-$$
$$-L_{obd}i_2(0)-\left[\frac{U_g}{P}+(L_g+L_{du})i_1(0)\right]R_{sh}+L_{obd}i_2(0)K_d=$$
$$=K_d L_{obd}i_2(0)-U_g L_{obd}--\frac{U_g R_{obd}}{P}-P(L_g+L_{du})i_1(0)L_{obd}- \tag{9}$$

$$-\left(L_g+L_{du}\right)i_1(0)R_{obd}-L_{obd}i_2(0)R_{sh}-\frac{U_g}{P}R_{sh}-\left(L_g+L_{du}\right)i_1(0)R_{sh}=$$
$$=K_dL_{obd}i_2(0)-P\left(L_g+L_{du}\right)i_1(0)L_{obd}-\frac{U_g}{P}(R_{obd}+R_{sh})-$$
$$-U_gL_{obd}-\left(L_g+L_{du}\right)i_1(0)R_{obd}-L_{obd}i_2(0)R_{sh}-\left(L_g+L_{du}\right)i_1(0)R_{sh}.$$

For the inverse Carson transformation of the image $I_1(\mathrm{P})$, its expressions must be multiplied by P. Then, according to [12-14].

$$I_1(\mathrm{P})=\frac{1}{L_{obd}\left(L_g+L_{du}\right)}\{\left[P^2\left(L_g+L_{du}\right)i_1(0)L_{obd}\right]+$$
$$+P[K_dL_{obd}i_2(0)-U_gL_{obd}-\left(L_{\text{г}}+L_g\right)i_1(0)R_{obd}- \tag{10}$$
$$-L_{obd}i_2(0)R_{sh}-\left(L_g+L_{du}\right)i_1(0)R_{sh}]-U_g(R_{sh}+R_{obd})\}$$

If ${\omega_0}^2>a^2$, then

$$i_1(t)=\frac{1}{L_{obd}\left(L_g+L_{du}\right)}\{-\frac{\omega_0}{\omega}e^{-at}\sin(\omega t-\theta)\left[\left(L_g+L_{du}\right)i_1(0)L_{obd}\right]+$$
$$+\frac{e^{-at}}{\omega}\sin\omega t[K_dL_{obd}i_2(0)-U_gL_{obd}-\left(L_g+L_{du}\right)i_1(0)R_{obd}-$$
$$-L_{obd}i_2(0)R_{sh}-\left(L_g+L_{du}\right)i_1(0)R_{sh}]- \tag{11}$$
$$-\frac{1}{{\omega_0}^2}\left[1-\frac{\omega_0e^{-at}\sin(\omega t+\theta)}{\omega}\left[U_g(R_{sh}+R_{obd}\right]\right],$$

where $\omega^2={\omega_0}^2-a^2$; $\tan\theta=\frac{\omega}{a}$.
If ${\omega_0}^2=a^2$, то

$$i_1(t)=\frac{1}{L_{obd}\left(L_g+L_{du}\right)}\{e^{-at}(1-at)\left[\left(L_g+L_{du}\right)i_1(0)L_{obd}\right]+$$
$$+te^{-at}[K_dL_{obd}i_2(0)-U_gL_{obd}-\left(L_g+L_{du}\right)i_1(0)R_{obd}-L_{obd}i_2(0)R_{sh}-$$
$$-\left(L_g+L_{du}\right)i_1(0)R_{sh}]-\frac{1}{{\omega_0}^2}\left[1-e^{-at}(1+at)U_g(R_{sh}+R_{obd}\right] \tag{12}$$

If ${\omega_0}^2<a^2$, то

$$i_1(t)=\frac{1}{L_{obd}\left(L_g+L_{du}\right)}\{\frac{1}{\mathcal{L}_1-\mathcal{L}_2}\left(\mathcal{L}_1e^{-\mathcal{L}_1t}-\mathcal{L}_2e^{-\mathcal{L}_2t}\right)\left(L_g+L_{du}\right)i_1(0)L_{obd}+$$
$$+\frac{1}{\mathcal{L}_1-\mathcal{L}_2}\left(e^{-\mathcal{L}_2t}-e^{-\mathcal{L}_1t}\right)[K_dL_{obd}i_2(0)-U_gL_{obd}-$$
$$-\left(L_g+L_{du}\right)i_1(0)R_{obd}-L_{obd}i_2(0)R_{sh}-\left(L_g+L_{du}\right)i_1(0)R_{sh}+$$
$$+\frac{1}{{\omega_0}^2}\left[1-\frac{{\omega_0}^2}{(\mathcal{L}_1-\mathcal{L}_2)}\left(\frac{e^{-\mathcal{L}_2t}}{\mathcal{L}_2}-\frac{e^{-\mathcal{L}_1t}}{\mathcal{L}_1}\right)\right]\left[U_g(R_{sh}+R_{obd}\right], \tag{13}$$

where $\mathcal{L}_1$, $\mathcal{L}_2$ are roots of the characteristic equation.

With values $\mathcal{L}_1 = 12{,}488$ G; and $\mathcal{L}_2$ =-30.314 G of the roots of the characteristic equation

Let us determine the parameters of the windings of the traction generator and TED. The inductance L_{obdr} of a real TED of the ED-118 type when operating in the AF mode, which corresponds to section I on the approximate magnetization curve [5], is determined from the equation:

$$L_{obdr} = \frac{\Delta\Phi}{\Delta i} = 13.67 \cdot 10^{-3}, \text{G}$$

Inductance L_{obdu} conditional TED:

$$L_{obdu} = \frac{13{,}67 \cdot 10^{-3}}{6} = 2.445\ 10^{-3}, \text{ G}$$

The inductance of the armature windings of the traction generator and TED is determined by the formula [4].

$$L_{ya} = 0.6 \frac{U_{nom}}{p\omega_{nom} I_{nom}} \quad (14)$$

$$L_{yag} = \frac{465}{5 \cdot 89.25 \cdot 4320} \cdot 0.6 = 0.14 \cdot 10^{-3}, \text{ G}$$

$$L_{yad} = 0.6 \cdot \frac{465}{2 \cdot 60.9 \cdot 720} = 3.18 \cdot 10^{-3}, \text{ G}$$

The inductance L_{dp} of the traction generator and conventional TED is determined by the formula [4]

$$L_{dp} = 0.65 \cdot 2 \cdot \sigma_k \cdot \Phi_k \frac{\omega}{i_{ya}}, \quad (15)$$

$$L_{dpg} = 0.82 \cdot 10^{-3}, \text{ G}; \qquad L_{dpd} = 0.15 \cdot 10^{-3}, \text{ G}$$

Conditional TED inductance L_{du}:

$$L_{du} = \frac{L_{yad} + L_{dpd}}{6}, \text{ G} \quad (16)$$

$$L_{du} = 0.53 \cdot 10^{-3}, \text{ G}$$

The value of the resistance of the armature circuit and the DP of the traction generator will be taken according to [5]

$$R_g = R_{dpg} + R_{ya}, \text{ Ohm} \quad (17)$$

$$R_g = 2.185 \cdot 10^{-3}, \text{ Ohm}$$

The value of the resistances of the resistors $R_{\text{ду}}$ and $R_{\text{шу}}$ will also be determined from [5]:

$$R_{du} = \frac{R_{du} + R_{dpd}}{6}, \text{ Ohm} \quad (18)$$

$$R_{du} = 3.52 \cdot 10^{-3}, \text{ Ohm}$$

$$R_{shu}^{op1} = \frac{R_{shr}^{op1}}{6}, \text{ Ohm} \quad (19)$$

$$R_{shu}^{op1} = 3.283 \cdot 10^{-3}, \text{ Ohm}$$

$$R_{shu}^{op2} = \frac{R_{shr}^{op2}}{6}, \text{ Ohm} \quad (20)$$

$$R_{shu}^{op2} = 1.533 \cdot 10^{-3}, \text{Ohm}$$

The coefficients $K_{shg}$and K_{shd}will be determined according to [6, 7]:

$$K_{shg} = 0.085,\ K_{shd} = 0.12 \text{ Ohm}$$

Calculate the coefficients B and C for the values:
$K_{shg} = 85 \cdot 10^{-3}\text{Ohm}$; $K_{shd} = 120 \cdot 10^{-3}\text{Ohm}$; $R_g = 2.185 \cdot 10^{-3}\text{Ohm}$; $L_{yag} = 0.14 \cdot 10^{-3}\text{G}$; $R_{du} = 3.52 \cdot 10^{-3}\text{Ohm}$; $L_{du} = 0.53 \cdot 10^{-3}\text{G}$; $R_{shu}{}^{\text{оп1}} = 3.283 \cdot 10^{-3}\text{Ohm}$; $L_{ovu} = 2.445 \cdot 10^{-3}\text{G}$; $R_{ovu} = 3.4 \cdot 10^{-3}\text{Ohm}$; $L_{gdp} = 0.82 \cdot 10^{-3}\text{G}$.
TED transfer coefficient $K_g = 1$ on the linear part of the magnetization curve and $K_g = 0.5$ (Fig. 1) behind its "knee", the value of B>0 and C>0, and B=104.011$\cdot 10^{-6}$, a C = $3352.679 \cdot 10^{-6}$ at K = 1 and C = $1679.5 \cdot 10^{-6}$ at $K_g = 0.5$ a = 14.275
Values

$$2a = \frac{B}{A} = 14.275 = 28.5 \qquad 2a = 14.275$$

$$\omega_0{}^2 = \frac{C}{A} = 920.03 \quad \text{by} \quad K_g = 1\ \omega_0{}^2 = 920.03$$

$$\omega_0{}^2 = \frac{C}{A} = 461.021 \ \text{by} \ K_g = 0.5 \ \ \omega_0{}^2 = 461.021$$

Thus the roots of the characteristic equation

$$\mathcal{L}_1,\ \mathcal{L}_2 = -14.275 \pm j26.763 \text{ at } K_g = 1$$

$$\mathcal{L}_1,\ \mathcal{L}_2 = -14.275 \pm j16.039 \text{ at } K_g = 0.5$$

3 Conclusion

The results of the above calculations confirm the inconsistency of the direct switching scheme, carried out according to the principle that the smaller the position of the regulator, the higher (relative to the setting at the nominal power of the DGU) the direct switching speed occurs. This principle has been violated since the creation of the TE10 diesel locomotive. It is violated to this day on TE10 diesel locomotives, except for diesel locomotives equipped with the USTA system.

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