

A technique analysis of ways to compensate high-frequency currents on traction electric machines mechanical units

Valery Zelentsov

RSVPU

Yekateringburg, Russia

v.zelentsov@gmail.com

Vladimir Ippolitov

RSVPU

Yekateringburg, Russia

vladimir.ippolitov@rsvpu.ru

Ignat Dyshevov

design development department

"Ural Locomotives"

Verkhnyaya Pyshma, Russia

ignat984@mail.ru

Abstract—the article is dedicated to the solution of the problem of high-frequency currents influence on the mechanical components of traction electric machines while their use. It gives the analysis and solution of the problem of high-frequency current compensation, which are confirmed by the results of field tests.

Keywords—*eddy currents, frequency, shunts (electrical), electrical engineering, electrostatic precipitators, transportation industry, capacitance, voltage measurement, frequency measurement, voltage control, electric variables control, grounding, filters, electricity, modeling.*

I. INTRODUCTION

A common problem of electric drives with semiconductor converters is the accelerated wear of the electric drive motor bearing units. Such damages are caused by the bearing currents formed in the traction motor, which can have a continuous or permanent effect on the bearing units, and as a result cause their breakdown because of the of spark-erosion [1], [2].

As it was found out during their running, all inverters generate common mode voltage related to the ground connection, which create coupled currents flowing through the motor parasitic capacitances to the rotor core. As the coupling currents pass through the motor bearings back to the grounded stator frame, they form so-called bearing currents. Thus, many scientific centers dedicated their work in this field to solving the problem of compensation or levelling these currents so that to exclude their effect on the mechanical components of drive asynchronous machines [3], [4].

Today the work on the problem of bearing currents has resulted in three main methods designed to prevent the appearance of high-frequency currents in bearings, that can be used separately or in combinations:

- special cable laying and grounding system;
- bearing currents elimination;
- damping of high-frequency common-mode interference.

All of them are designed to reduce the voltage through the lubrication of the bearings to the proportions that do not cause high-frequency current pulses in the bearings or reduce the ripple value to a level that does not affect the service life of the bearings [5].

The basis of all high-frequency currents problem solutions is a proper grounding system. The rules for operating the standard equipment grounding are mainly designed to ensure a sufficiently low connection resistance, to protect people and equipment from insulation breakdowns in the supply network. A variable-speed motor can be effectively grounded to limit high-frequency common-mode interference currents if the setting follows the following rules [6], [7]:

- use of insulated bearings. As a matter of practice the insulation of some types of bearings of different thicknesses and in different places (for example, between the shaft and the inner ring of the bearing, between the outer ring of the bearing and the housing) is commonly used. Generally accepted are anti-friction bearings with a ceramic coating on the outer surface (the so-called bearings with an anti-friction coating). Bearings with ceramic rotation elements are also suitable;
- use of a filter that reduces common-mode interference voltage and/or dU/dt ;
- use of non-conductive connections for termination or other devices that may be damaged by currents through the bearings;
- use of brush contacts between the shaft and the motor housing;
- use, if possible, of a motor and a low-voltage converter;
- start the converter at the lowest switching frequency that meets the noise and temperature requirements;
- elimination of double edges (parallel wiring).

II. THE HIGH-FREQUENCY CURRENT COMPENSATION PROBLEM: ANALYSIS AND SOLUTION

Today, with the land transport development and the adoption of new environmental standards, equipment manufacturers around the world are tending to use asynchronous electric machines as traction drives. Every manufacturer, when working to improve the operational reliability of their products, sooner or later faces the prospect of failures of asynchronous electric drives due to bearing currents.

The work of OOO "Ural Locomotives" has resulted in the development and testing in practice of a number of

devices aimed at minimizing the likely negative impact of bearing currents on the mechanical components of traction electric motors of the *Lastochka* electric train.

As part of our research work, we draw an electric train replacement circuit (Fig. 1), and then selected and calculated the parameters of the elements introduced into the replacement circuit in such a way that it could reduce the volume of bearing currents to a level that does not lead to the metal spark-erosion and lubrication oxidation in the asynchronous traction electric machines mechanical components.

Figure 1 shows the following elements: Z_1 - the electrical impedance of the section in the path of the current flow I_1 ; Z_2 - the electrical impedance of the second truck in the fifth carriage; Z_5 - the electrical impedance of the second truck in the first carriage; Z_6 - the electrical impedance of the section in the path of the current flow I_6 ; R_{sh} - DCR in the shunt connecting the electric train body and its negative bus; R_{5-0} - DCR of the electric train body in the section between the second truck of the fifth carriage and the shunt connecting the electric train body and the negative bus a; R_{1-0} - DCR of the electric train body in the section between the second truck of the first carriage and the shunt connecting the electric train body and the negative bus; I_{N5} - current induced on the fifth carriage; I_{N1} - current induced on the first carriage; E_5 - induced voltage on the fifth carriage; E_1 - induced voltage on the first carriage.

Taking into account the technical requirements for the traction motor, we selected FAG current-insulating rolling bearings.

With an electric current flowing through FAG 6016-M-j20a bearing, which insulation in the static state is designed for 1000 V, shows the properties of a capacitor. As the voltage frequency increases, the resistance of the capacitor changes from 5-9 ohms to several ohms.

The scheme demonstrating the dependence of the resistance on the frequency of the applied voltage is shown in figure 2 [8].

To calculate the electrical replacement circuit, we measured the hollowing electric train parameters:

1. Electrical capacity;
2. Active resistance of various body sections.

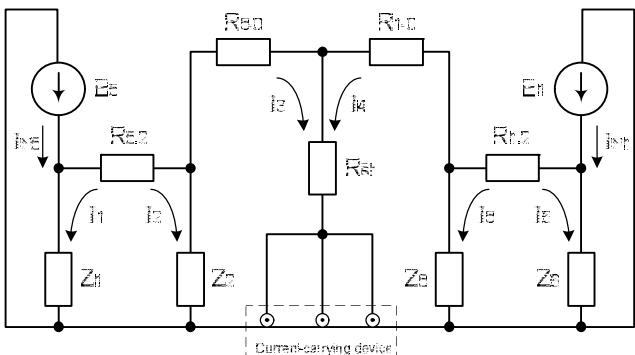


Fig. 1. A design layout of electric train power supply equivalent circuit

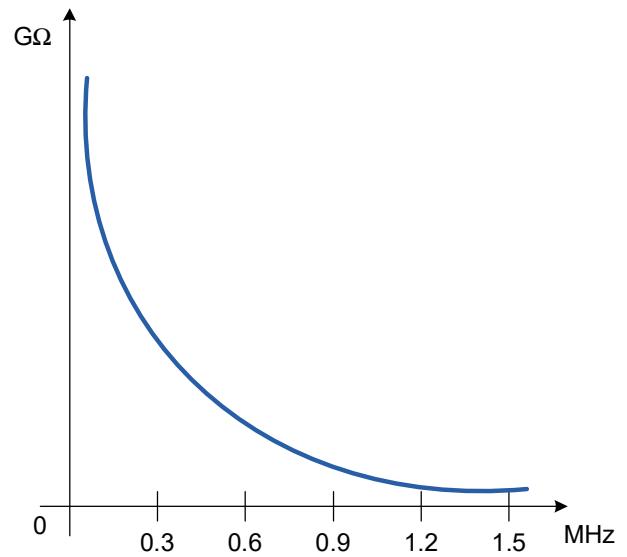


Fig. 2. The dependence of the bearing resistance on the frequency of the voltage applied

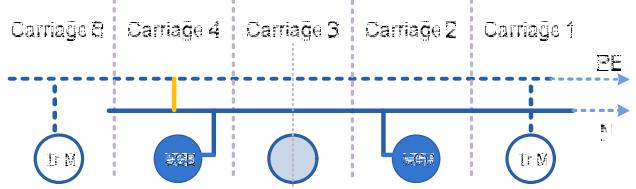


Fig. 3. Electric train grounding block schematic diagram

The main feature of the electric train grounding circuit design is its asymmetry (see Fig. 3), where all five cars are connected to each other electrically, and there is a connection with the current removal device only on carriage 4. Based on this, the calculation of the percentage of induced currents distribution in the grounding system and the probability of its flowing through the traction motors bearings on the head carriages was figured out.

The calculations took the following factors into consideration:

1. The inductance of the circuit is not taken into account due to its insignificance.
2. The electric current I_{N5} induced on the fifth carriage does not flow through the branches Z_5 and Z_6 resistances. Similarly, the electric current I_{N1} induced on the first carriage does not flow through the branches with Z_1 and Z_2 resistances. Mathematically, this can be shown by the following formulas:

$$I_{N5} = I_1 + I_2 + I_3; \quad (1)$$

$$I_{N1} = I_4 + I_5 + I_6. \quad (2)$$

The core-gear voltage corresponds to the one measured during the tests: 350 V 750 Hz.

The calculation of the percentage of induced currents I_{N5} and I_{N1} distribution on the branches is carried out separately, so that the current I_{N5} is taken as 100%. Similarly I_{N1} is also taken as 100%.

The induced voltage on the first carriage is equal to the induced voltage on the fifth carriage:

$$E_1 = E_5. \quad (3)$$

The resistance values shown in figure 1 are calculated using the following formulas:

$$Z = \sqrt{R^2 + Xc^2}; \quad (4)$$

$$Xc = \frac{1}{2\pi f C}. \quad (5)$$

Based on these data, we calculated the distribution percentage for the currents induced on the first and fifth carriages:

$$I_1 = \frac{E_5}{Z_1}; \quad (6)$$

$$I_2 = \frac{E_5 - \left(\frac{E_5}{R_{5.2} + \left(\frac{Z_2 * (R_{5-0} + R_{sh})}{Z_2 + R_{5-0} + R_{sh}} \right)} * R_{5.2} \right)}{Z_2}; \quad (7)$$

$$I_3 = \frac{E_5 - \left(\frac{E_5}{R_{5.2} + \left(\frac{Z_2 * (R_{5-0} + R_{sh})}{Z_2 + R_{5-0} + R_{sh}} \right)} * R_{5.2} \right)}{Z_{5-0} + R_{sh}}; \quad (8)$$

$$I_4 = \frac{E_1 - \left(\frac{E_1}{R_{1.2} + \left(\frac{Z_5 * (R_{1-0} + R_{sh})}{Z_5 + R_{1-0} + R_{sh}} \right)} * R_{1.2} \right)}{Z_2}; \quad (9)$$

$$I_5 = \frac{E_1 - \left(\frac{E_1}{R_{1.2} + \left(\frac{Z_5 * (R_{1-0} + R_{sh})}{Z_5 + R_{1-0} + R_{sh}} \right)} * R_{1.2} \right)}{Z_5 + R_{1-0} + R_{sh}}; \quad (10)$$

$$I_6 = \frac{E_1}{Z_6}. \quad (11)$$

The percentage for current I_1 to the current I_5 is:

$$i = \frac{I_1}{I_1 + I_2 + I_3} * 100%. \quad (12)$$

Substituting formulas 6, 7, and 8 into formula 12 and converting the resulting expression, we get the following:

$$i = \frac{Z_2 + Z_3}{Z_2 * Z_3 + Z_1 \left(1 - \frac{1}{R_{5-2} + \frac{Z_2 * (R_{5-0} + R_{sh})}{Z_2 + R_{5-0} + R_{sh}}} \right) * (Z_2 + Z_3)} * 100%. \quad (13)$$

Substituting the resistance data, and finding the I_2, I_3, I_4, I_5, I_6 currents in the same way, we calculated the percentage for current distribution. The results are presented in table 1.

TABLE I. THE PERCENTAGE FOR INDUCED CURRENT DISTRIBUTION

Carriage 5		Carriage 4		Carriage 1	
$I_1, \%$	$I_2, \%$	$I_3, \%$	$I_4, \%$	$I_5, \%$	$I_6, \%$
0.0003	0.0003	99.9994	99.9982	0.0009	0.0009

It can be concluded that the electrical impedance of sections 1, 2, 5 and 6 are many times higher than the one of sections 3 and 4. Therefore, the volume of the bearing currents is so small that it does not lead to spark-erosion. It should be noted that the currents I_5 и I_6 are three times higher than the currents I_1 и I_2 , so to ensure reliable work of the bearings in the first carriage, it is necessary to ensure that the amount of current flowing through them is at the level of the bearing currents in the fifth carriage.

The statistical evidence shows that if the volume of the bearing currents in the first carriage is kept equal to or close to the level of the bearing currents in the fifth carriage, it is possible to avoid the bearings damage due to the flow of electric current through them. At the initial stage, to level up these currents we tested the hypothesis of the possible using of an additional grounding bus in carriage 2, as well as the possibility of using a stainless steel cable instead of a copper shunt there.

The analysis of the technical publications shows that one of the most common measures to eliminate high-frequency induced voltage is the use of a high-frequency interference suction filter [9], [10]. The analysis of the technical publications shows that one of the most common measures to eliminate high-frequency induced voltage is the use of a high-frequency interference suction filter [9], [10]. As the frequency of the induced voltage increases, the total resistance of the filter decreases, which allows the filter to take most of the current that occurs in the system. Thus, a suction filter with a total capacity of 44 UF was made up in the Simulink environment.

The design carried out in the Simulink graphical programming environment confirmed the experimental data on the effectiveness of using an additional shunt for grounding the electric train body to reduce the currents flowing through the motor-rotor bearings of the first carriage [11].

When installing an additional grounding shunt that has a resistive impedance, there is a possibility of a tractive current flowing through the electric train body from an electric rolling stock following the same feeder section. The flow of traction current will inevitably lead to excessive heating of the cables screens and shunts connecting the body to the electric train negative bus. The flow of traction current through the train impairs electromagnetic compatibility and can cause failure of other systems and devices used on the electric train. Besides, high-ampere currents flowing through the electric train body may lead to the load-bearing parts spark-erosion and their following destruction. Thus, it is necessary to carry out some additional works when implanting a shunt with a resistive impedance on the second carriage, to protect the electric train body [6].

The installation of a high-frequency interference suction filter helps to avoid additional protective measures, since the filter is a set of capacitors that prevents constant flow of traction current through the filter when driving in areas electrified with direct current.

III. TEST RESULTS

Based on the above, in order to protect the traction electric motors motor-rotor bearings from the flow of bearing currents, it was decided to conduct full-scale tests

with the installation of a high-frequency interference suction filter on the second carriage of the electric train. For this purpose, we made a metal container that by its weight and size characteristics was suitable for installation in the sub-car space of the electric train second carriage, and also matched the internal volume of the suction filter design. Then we selected an on-the-road electric train that met the only criterion – problem-free functioning of all components. When installing the electric train carriage 2 in the sub-car space, we additionally analysed the effect of the suction filter installation on the main equipment layout.

To register the parameters we used a data acquisition system consisting of an analog-to-digital converter and current and voltage sensors. The parameters were recorded with a sampling frequency of 100 kHz.

When conducting field tests, it was found that the voltage on the traction motor bearing (Fig. 4) was very little (not beyond the error of the meter). This was due to the use of the suction filter, in the circuit of which there was a current of up to 54A.

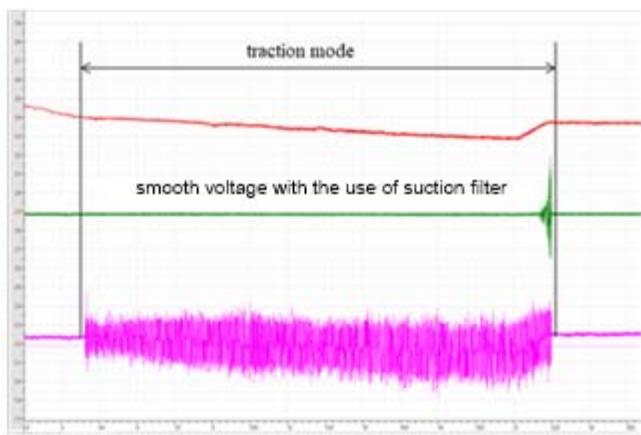


Fig. 4. Test results with the suction filter installed:
 - redcolour → catenary voltage;
 - greencolour → traction motor bearing voltage;
 - pinkcolour → the suction filter current

To illustrate the difference more clearly, the previously obtained waveforms without the suction filter use are shown in figure 5.

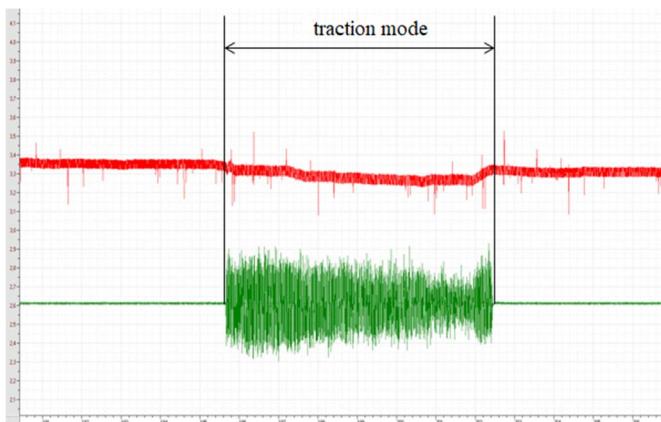


Fig. 5. Test results without the suction filter installed:
 - redcolour → catenary voltage;
 - greencolour → traction motor bearing voltage

IV. CONCLUSION

When conducting field tests, the use of a suction filter proved its effectiveness in levelling the voltage on the asynchronous traction motor bearing in the current removal system of the tested Lastochka electric train. We believe that the use of such system will undoubtedly provide a certain cost advantage, which in turn will improve the quality of products, as well as improve their performance characteristics. Our further work in this area will be aimed at testing the compatibility of the suction filter with other electric train systems and framework equipment. As a result of these tests, the possible using of a suction filter as an additional equipment designed to prevent premature failure of mechanical components of traction motors due to bearing currents will be taken into consideration and this may resolve the problem in the future.

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