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The increase of electric energy efficiency of the electric locomotives "Uzbekistan-yulovchi" in asymmetric modes

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ABSTRACT.The article deals with the issues of improving the energy performance of mainline locomotives with asynchronous motors by using the method of controlling the traction asynchronous motor according to the criterion of the minimum electrical power loss with the source voltage asymmetry, which reduces the electrical losses in the traction asynchronous drive over the entire range of operating power.

KEYWORDS: voltage asymmetry, side frequency bands, axial power, rational algorithm, amplitude-frequency control, asymmetric modes, contact network, four-quadrant converter

I. INTRODUCTION

Currently, there is a need to identify the state of traction asynchronous electric motors during their operation. Timely detection of damage caused by asymmetric modes will avoid further development of the process, reduce recovery time, reduce maintenance costs, avoid equipment downtime, and increase the efficiency of traction motors. Therefore, the study of asymmetric modes of asynchronous traction electric motors of locomotives of the "Uzbekistan-yulovchi" series is a scientific and practical task.

II. METHODS

To calculate the energy indicators of electric locomotives with a frequency-controlled traction motor, the motor current signature was analyzed, which is based on the detection of current harmonics with changed frequencies, which distinguish each category of voltage asymmetry, distortion of the rotor current distribution and, consequently, changes in the stator magnetomotive force. When the frequency decreases during regulation, all characteristics of the asynchronous traction motor deteriorate. This deterioration becomes especially noticeable when the rotor current frequency reaches below the nominal value. To reduce electrical power losses at frequencies different from the nominal, it is proposed to use a method for controlling a traction asynchronous motor according to the criterion of minimum electrical power losses in asymmetric modes.

The energy efficiency of electric traction of electric locomotives is a key indicator on which the possibility of realizing high-speed train traffic and ensuring and implementing the planned indicators depends. An increase in the voltage value in the alternating current catenary is caused by overestimated losses of voltage, active power in the contact network and in the traction drive of electric locomotives [1].

Analysis of statistical data on the reliability of the asynchronous traction main-line electric locomotives "Uzbekistan-Yulovchi" shows that from 16% to 21% of the damage occurs in the traction motor. Of all the damages, 67% are due to the insulation of the stator windings, 22% are associated with melting or breaking of rotor rods, 11% are caused by other reasons (mainly the bearing assembly).

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Improvement of traction electric drive performance is possible provided that a traction electric drive automatic control system is created, which ensures the implementation of all traction and energy characteristics of the locomotive, achievable through the use of progressive three-phase traction motors.

To maintain a minimum of electrical power losses in a wide range of values of the load torque, it is necessary to increase the rotor current and magnetic flux as the load on the motor increases. For locomotives with asynchronous traction motors and static frequency converters, the most favorable operating mode is the maximum condition.

The efficiency of asynchronous motors is known that a given motor load torque is realized by the magnetic flux and the active component of the rotor current, the ratio of which determines the value of the electrical power losses in the AM, the ratio between the magnetic flux and the rotor current, when the stator current becomes minimum at a constant load torque. To ensure this condition, it is necessary to select for each value of the load torque the appropriate values of the magnetic flux and frequency of the rotor current [4].

When operating asynchronous motors, an unbalance of the supply voltages may occur due to the asymmetry of the network load in phases or due to emergency situations. The analysis of the motor current signature is based on the detection of current harmonics with frequencies that distinguish each category of asymmetry.

Broken rods cause rotor asymmetry, distortion of the rotor current distribution and, consequently, changes in the rotor's magnetomotive force (MRF). Damage to rotor bars has a distinctive frequency response that can be calculated as:

$$f_{brb} = f_s(1 \pm 2ks)k = 1,2,3 \dots \dots (1)$$

the motor slip can be calculated as:

$$S = \frac{f_{slip}}{f_{sync}} = \frac{2f_s/p - f_r}{2f_s/p} \quad (2)$$

where f_s and f_r are the frequency at the output of the inverter and the motor speed, respectively,

p is the number of poles.

If the rod is damaged, it can be expected lateral frequency changes around the supply frequency. As a result, sidebands (harmonics) of the first order (k=1) are of particular importance in fault detection of a damaged rod. The left sideband $f_s(1\text{-}2ks)$ is due to electrical or magnetic asymmetry in the rotor current caused by damage to the rotor bars, while the right sideband $f_s(1+2ks)$ is due to speed ripple or vibration.

Sidebands of the rotor current frequencies can be observed when the electric motor does not have damaged rotor bars. This is due to shaft misalignment, which can, to a certain extent, cause an asymmetry of the rotor field.

However, the amplitudes of the side stripes generated in these cases are much smaller compared to those that occur with damaged rotor bars. Influence on the operation of the asynchronous traction motor of the “Uzbekistan-Yulovchi” electric locomotives. The power supply system is provided through a four-quadrant 4qS converter with pulse-width modulation control, which provides a decrease in $\cos\varphi$ in the consumption mode and an increase in $\cos\varphi = \pi$ in the power recovery mode.

Currently, methods based on operational data obtained from active and reactive energy meters are used to calculate power losses and consumed reactive power. The use of these data can lead to large errors, therefore, analytical methods of calculation based on the theory of circuits are being improved for the steady and dynamic modes of operation of asynchronous motors. The development of these methods makes it possible to correctly choose the type and parameters, the method of controlling an induction motor capable of responding to instantaneous changes in the value of the consumed reactive power.

To improve the energy efficiency and electromagnetic compatibility of the traction drive of the “Uzbekistan-yulovchi” electric locomotive with the power supply system, it is necessary to take into account the duration of the use of the electrical potential of the contact network for train traction and the spectrum of harmonic components of non-sinusoidal voltage and current at the electric locomotive pantograph.

Asymmetry worsens the operating conditions of asynchronous motors, reduces the resulting torque and, as a result, increases power losses.

When calculating the energy indicators of electric locomotives with a frequency-controlled traction motor, it is necessary to analyze the signature of the motor current, which is based on the detection of current harmonics with changed frequencies, which distinguish each category of voltage unbalance, distortion of the rotor current distribution and, consequently, changes in the stator magnetomotive force.

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In an asynchronous traction motor, magnetization (excitation) is carried out along the main magnetic (stator) circuit, due to which, with frequency control, the power consumption for magnetization can exceed 5% of the rated power. In this case, the magnetization of the asynchronous traction motor can also be maintained when the electric locomotive is freewheeling, i.e. with increased idling losses.

Thus, when the frequency decreases during regulation, all characteristics of the asynchronous traction motor deteriorate. This deterioration becomes especially noticeable when the rotor current frequency reaches below the nominal value.

Pulse Width Modulation (PWM) applications provide an almost sinusoidal voltage waveform to the motor. The use of PWM does not eliminate the problem of additional losses, and an increase in the frequency of the PWM carrier leads to an increase in dynamic losses in the power switches and the complication of negative wave processes in the asynchronous motor-frequency converter system [4].

When using inverters based on fully controlled IGBTs, converting the output voltage into a sequence of high-frequency square-wave pulses with a steep front (PWM), negative wave processes lead to failure of the stator winding insulation after 2 ... 3 years of operation.

Non-sinusoidal voltage during frequency regulation of induction motors leads to additional losses in the windings and magnetic circuit from the action of higher harmonics of current and magnetic flux created by higher harmonics of the supply voltage [3].

However, this conditional boundary of the decrease in the quality of the characteristics of a traction induction motor depends on its design parameters, mainly on the value of the active resistances of the stator windings, as well as the carrier frequency of the pulse-width modulation of the voltage.

To reduce the ripple of the traction torque of the asynchronous traction motor, it is necessary to stabilize the voltage at the inverter output. This is accompanied by an increase in power losses and reduces the efficiency of the electric locomotive.

At frequencies above the nominal, the efficiency can be assumed constant. Even a small level of voltage unbalance at the terminals of induction motors, due to the low resistance of their negative sequence, leads to a significant increase in active power losses, which in turn causes additional heating of the windings. Additional losses in electrical machines caused by voltage unbalance can be represented as [3].

$$\Delta P = k^{'} K_{2U}^{2} P_{H} (3)$$

where $k^{'}$- is the coefficient depending on the type of electric machine;
K_{2U}^{2} – coefficient of voltage unbalance;
P_H – rated active power of the motor;
For asynchronous motors, the coefficient k` is calculated as follows:

$$k_{AM}^{'} = 2{,}41 k_{AM} (4)$$

where k_{AM} – dimensionless factor that depends on the specific parameters of the engine (rated power, copper loss of the stator, the ratio of starting current).

The value of the k_{AM} coefficient is inversely proportional to the value of the rated power of the asynchronous motor. The average values of k_{AM} for various industries vary from 1.07 to 2.91, and for the entire industry, in general, it is recommended to take $k_{AM} = 1.85$ [4].

It should be noted that the additional active power losses due to the voltage asymmetry do not depend on the motor load and are determined from the expression, taking into account [3].

$$\Delta P_{EXT.AM} = 2{,}41 k_{AM} K_{2U}^{2} P_{H} (5)$$

Deviation from the optimal frequency of the rotor current in the direction of large values with a constant load moment leads to an increase in the input current of the inverter, and therefore to an increase in the current of the transistors. If the frequency of the rotor current is reduced by increasing the voltage at the specified values of the stator current frequency and the load moment, the input current of the inverter first decreases with increasing phase current, and then increases sharply.

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The amount of power loss from the action of a single current harmonic depends on its effective value and on the active resistance provided by the winding to this current harmonic. The active and inductive resistances of the asynchronous motor windings are different for each harmonic.

To calculate additional power losses from the action of the entire spectrum of harmonics, it is necessary to take into account the dependence of the resistances of the asynchronous motor on the frequency. The calculation of these dependences will allow us to take into account the real distribution of the current density and the value of the flux coupling of the winding.

The deviation of the frequency of the rotor current in the direction of smaller values leads to an increase of electric power losses in AM, and the deviation in a big way to increase the stator current due to the increase in the rotor current at small values of the magnetic flux, which leads to an increase of electrical losses. To maintain a minimum of electrical power losses over a wide range of load moment values, it is necessary to increase the rotor current and magnetic flux as the motor load increases.

A sharp increase in the input current of the inverter at low frequencies of the rotor current is explained by the saturation of the magnetic circuit of the motor. Taking into account the obtained data, the minimum power loss of the ΔPain electrical losses in the autonomous inverter (AIN) are calculated);

ΔPsteel - electrical losses in the steel;

ΔPr-electrical losses in the rotor winding;

ΔPs electrical losses in the stator winding;

ΔPhth electrical losses from the higher time harmonic components of the current.

Thus, the sum of losses in an asynchronous motor is defined as:

$$\Delta P_{\Sigma} = U\frac{Rr+Lr\omega-2Lr\omega r\omega n+Lr\omega n}{[RrRs-(\omega s-\omega n)\omega s(LsLn-Ln)]}Rs+\left(\frac{Pr}{\omega n}\frac{\omega s-Zp\omega n}{ZpRr}\right)Rr+\Delta Ps \quad (6)$$

To reduce electrical power losses at frequencies other than the nominal ones, it is proposed to use a method for controlling a traction asynchronous motor according to the criterion of minimum electrical power losses in asymmetric modes.

III. RESULTS AND DISCUSSIONS

When studying the asymmetric modes of asynchronous motors, we considered the operation of a symmetrical motor at an asymmetric supply voltage and the operation of an asymmetric motor at a symmetrical supply voltage (usually the motor is asymmetric along the stator or rotor). Although the asymmetric modes differ from each other, the mathematical descriptions of the energy conversion processes in both cases are close to each other. The most general and more complex is the study of an unsymmetric asynchronous motor with an unsymmetric supply voltage from the asynchronous motor supply via a 4qS four-quadrant converter.

IV. CONCLUSION

Increasing the energy performance of the electric locomotive "Uzbekistan-yulovchi" in asymmetric modes is possible while maintaining a minimum of electrical power losses in a wide range. To reduce electrical power losses at frequencies other than the nominal ones, it is proposed to use a method for controlling a traction asynchronous motor according to the criterion of minimum electrical power losses in asymmetric modes.

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