

THE DETERMINATION OF THE ASYNCHRONOUS TRACTION MOTOR CHARACTERISTICS OF LOCOMOTIVE

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DOI: 10.15598/aeee.v15i2.1926

Abstract. *The article deals with the problem of the locomotive asynchronous traction motor control with the AC diesel-electric transmission. The limitations of the torque of the traction motor when powered by the inverter are determined. The recommendations to improve the use of asynchronous traction motor of locomotives with the AC diesel-electric transmission are given.*

The development of algorithms and principles of the control system, the improving of the pull and energy characteristics of locomotives to increase the effectiveness of their operation are the main directions of research in the field of improvement of the locomotives power transmission.

The optimization of the locomotives traction characteristics to better harness the advantages of the used traction motors is one of the most urgent issues.

The work in the field-weakening mode in a significant speed range is one of the work features of the locomotive asynchronous traction motor. The article examines the formation of characteristics of the asynchronous traction motor working in such conditions.

Keywords

AC traction motor, diesel-electrical locomotive, diesel-electrical transmission.

1. Introduction

Currently, the update of the locomotive fleet, including the fleet of freight locomotives is carried on the railways of the Russian Federation. The locomotives with asynchronous traction motors are considered to be promising in accordance with the technical policy of the industry [1]. The batch of the freight locomotives 2TE25A "Vityaz" is released. The first new experience of the locomotives operating has shown that some of the technical solutions require further, more in-depth elaboration.

2. The Problem Statement

The use of the asynchronous traction motor on the traction rolling stock is related to the number of limitations. It is particularly true for diesel locomotives, where the diesel electrical transmission with AC machines is used.

One of the most promising locomotives is a new freight locomotive with asynchronous traction motor 2TE25A [1], [2] and [3]. It has the diesel generator set of 2500 kW capacity in each six-axle section. Each of the two three-phase stator windings of the synchronous

traction generator feeds the appropriate traction converter. Each converter includes uncontrolled bridge rectifier and three autonomous voltage inverters. Each asynchronous traction motor receives the power from its self-commutated voltage inverter. Therefore, the individual (by each axis) regulation of traction is realized. It improves the locomotive haulage capacity.

The output voltage of autonomous voltage inverter is limited and depends on the voltage in the DC link. Permissible heating windings and inverter of the IGBT-modules limit the phase current of asynchronous traction motor. The coupling conditions in contact "wheel - rail" limit the torque of the traction motor. In the formation of the traction motor characteristics it is necessary to take into account the saturation of its magnetic system, limiting rotor flux linkage. The voltage on the DC link (at the inverter input) is not constant and depends on the speed of the diesel generator, which varies over a wide range.

The rotation of the rotor of the asynchronous traction motor varies widely when the locomotive works. It is necessary to take it into account when creating the System of the Automatic Control (SAC). Two modes of the traction motors can be defined: the torque limit mode and the power limit mode.

The torque limit mode is used at low speed. The rotor flux linkage is maintained at a constant level, it is independent of the rotor speed of the asynchronous traction motor. The torque value is limited to the conditions of the clutch and the amount of current consumed by the converter of the asynchronous traction motor.

The back-EMF of the motor is increasing with speed increase and there is an increase of the output voltage of autonomous voltage inverter. The torque limit mode is possible up to a speed at which the output voltage of the inverter becomes maximum possible with the used modulation method. The limitation of inverter voltage does not allow regulation at constant flux linkage and requires the use of field weakening.

With further speed increase, the stator voltage remains constant and equal to its maximum value, which the inverter limits. The stator current may not exceed the nominal one, which the current load on the power semiconductors of the inverter determines.

Thus, in these modes the regulation of asynchronous traction motor should be carried out at a constant voltage and a constant current of the stator, which corresponds to the implementation of the law of the constancy of the full power supplied to the stator. This law allows the best use of electrical equipment of the locomotive and it is optimal in terms of traction properties.

Therefore, according to the theory of electrical machines, the traction motor operation takes place in two zones: in a constant field zone and in a weak field zone.

3. The Mathematical Description of Processes in an Asynchronous Traction Motor

As known [4], [5] and [6], the predetermined electromagnetic torque on the asynchronous traction motor shaft can be obtained by various values of the rotor flux linkage. The flux linkage increase reduces the stator current; it reduces the current load on IGBT-modules of the inverter. However, the flux linkage growth above the nominal value leads to the saturation of the magnetic system of the asynchronous traction motor and to the significant increase of the magnetic losses. In addition, stator current component significantly increases on the d-axis, which may lead to the stator current increase, instead of its reduction. Therefore, in the control zone without field weakening, it is advisable to implement an asynchronous traction motor control with a nominal flux linkage.

The equations in the $d - q$ coordinate system describe the processes in the stator winding of the asynchronous traction motor. The engine is operated with the use of vector control principles and the rotor flux linkage vector is directed along the d -axis: $\Psi_r = \Psi_{rd} = \text{const}$, $\Psi_{rq} = 0$. In this case, the equations system for the projection of the stator current vector on the axis of the rotating $d - q$ coordinate system is following:

$$\begin{cases} L'_s \frac{dI_{sd}}{dt} = U_{sd} - R_s I_{sd} + L'_s p \omega i_{sq}, \\ L'_s \frac{dI_{sq}}{dt} = U_{sq} - R_s I_{sq} - L'_s p \omega i_{sd} - p \omega \frac{L'_m}{L_r} \Psi_{rd}, \end{cases} \quad (1)$$

where L_m - magnetizing inductance of the asynchronous traction motor; $L'_s = L_s \cdot \left(1 - \frac{L_m^2}{L_s \cdot L'_r}\right)$ - total leakage inductance from the stator; $L_{\sigma s}, L_s = L_m + L_{\sigma s}$ - leakage inductance and the total inductance of the stator; $L'_{\sigma r}, L'_r = L_m + L'_{\sigma r}$ - leakage inductance and the total inductance of the rotor, referred to the stator; R_s - stator resistance.

Given that $\Psi_{rd} = L_m \cdot I_{sd}$, the electromagnetic torque is determined using the expression:

$$M_{em} = \frac{3}{2} \cdot p \cdot \frac{L_m}{L'_r} \cdot \Psi_{rd} \cdot I_{sq} = \frac{3}{2} \cdot p \cdot \frac{L_m^2}{L'_r} \cdot I_{sd} \cdot I_{sq}. \quad (2)$$

Absolute slip (rotor current frequency) is determined by the formula:

$$\omega_r = I_{sq} \cdot \frac{L_m R'_r}{L'_r \cdot \Psi_{rd}}, \quad (3)$$

where R'_r - rotor resistance referred to the stator.

Figure 1 shows a vector diagram of asynchronous traction motor in the traction mode, where the following notations are given: θ - the angle of the rotor rotation in electric space; δ - the angle between the rotor flux linkage and the stator current (load angle); φ - the angle between the vectors of the stator voltage and current; $\vec{E} = p \cdot \omega \cdot \vec{\Psi}_r$ - EMF vector of the stator induced by the rotor flux.

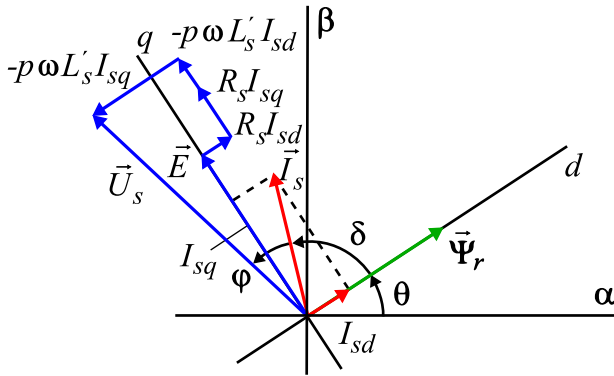


Fig. 1: The vector diagram of asynchronous traction motor in the traction mode.

In the locomotive under consideration, the asynchronous traction motor of the AD-917 type with the following parameters is installed:

- $p = 3$,
- $L_m = 0.01238$ H,
- $L_{\sigma s} = 0.001405$ H, $L'_{\sigma r} = 0.000913$ H,
- $R_s = 0.03$ Ω , $R'_r = 0.0274$ Ω .

The basic data of the traction motor AD-917 are following:

- $U_{ln} = 605$ V (1150 V) – the linear voltage for a long period (maximum),
- $I_{sn} = 440$ A (480 A) – the phase current of a long operating mode (starting),
- $f_{sn} = 18.6$ Hz (125 Hz) – stator current frequency for a long operating mode (maximum),
- $M_n = 10\,200$ Nm – shaft torque in a long operating mode,
- $\Psi_{rd} = 4.18$ Wb – the rotor flux linkage in a long operating mode.

The values of voltage and current of the stator, the rotor flux linkage are given as actual values.

4. Characteristics of the AC Traction Motors

The traction characteristic of the locomotive has two zones. In the first one the torque of asynchronous traction motor is limited by clutch conditions. In the second zone the torque is determined by the constancy of power. At the transition from the first to the second control zone, the speed value is determined by the torque value in the starting mode and the power of the diesel generator set.

In some cases, at this speed the output voltage of a diesel generator set reaches its maximum value, but this condition is not mandatory. On the locomotive under consideration, the diesel generator set voltage reaches the maximum value at the speed more than the speed of the transition to the power limit. Thus, three zones can be distinguished in the regulation characteristic of the asynchronous traction motor on the locomotive.

In the speed range from zero to the diesel generator set full power speed, the traction motor implements torque that is equal to starting one (the first control zone). The voltage applied to the stator winding rises to a value smaller than maximum. With further increase of the speed, there is the reduction of torque to maintain the power constancy law (the second control zone). The voltage applied to the stator winding continues to increase. When it reaches the maximum value that is limited by inverter, the motor goes into the field-weakening operation mode (the third control zone).

As it is known, the electromagnetic torque of the asynchronous traction motor can be obtained by various combinations of the stator current components along the d and q axes [3], [4], [5], [6], [7] and [8]. The specified torque is realized with the least current of the stator when these components of the current are equal [3], [4], [5] and [6]. The operation with a minimum of stator current leads to a considerable increase of the rotor flux linkage and causes strong saturation of the magnetic system at the starting mode of the asynchronous traction motor AD-917. The flux linkage is equal to the nominal value during operation with the long operating mode torque when calculating the characteristics of asynchronous traction motor.

At steady mode, taking into account Eq. (1) the vector projection, the stator voltage on the d and q axes are equal:

$$\begin{aligned} U_{sd} &= R_s \cdot I_{sd} - L'_s \cdot p \cdot \omega \cdot I_{sq}, \\ U_{sq} &= R_s \cdot I_{sq} + L'_s \cdot p \cdot \omega \cdot I_{sd} + p \cdot \omega \cdot \frac{L_m}{L'_r} \cdot \Psi_{rd}. \end{aligned} \quad (4)$$

In the speed range from zero to the speed of transition to the power limit mode (the first control zone),

the given torque and value of the rotor flux linkage determines the stator current, the formula determines the required voltage stator:

$$U_s = \sqrt{U_{sd}^2 + U_{sq}^2}. \quad (5)$$

The torque of the asynchronous traction motor decreases when the speed exceeds the speed of transition in the power limitation mode, in the second control zone. The flux linkage value of the rotor is also reduced when a predetermined torque is realized with a minimum of stator current. The magnetic field of the motor slightly reduces.

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In the third control zone, the control of the asynchronous traction motor is carried out when the torque is maximum and when the current and the stator voltage are restricted. The load angle value is determined in accordance with this condition.

As it has been noted, the work with a deep field weakening is a feature of use of the asynchronous traction motor in the locomotive. In this mode it is necessary to control the position of the operating point on the mechanical characteristics of the asynchronous traction motor; it must be within the ascending branch (motor slip should be less than critical). It provides the stable motor work. The ratio of the critical points to

the current torque must not be less than a predetermined value. The ensuring of the sustainability of the asynchronous traction motor is relevant at high speeds in the third control zone. The Kloss specified formula can determine the rotor current frequency at which the required ratio of the critical moment to the current value is implemented [9]:

$$\frac{M_{emM}}{M_{em \max}} = \frac{2 + 2 \cdot q}{\frac{\Omega_r}{\Omega_{r \max}} + \frac{\Omega_{r \max}}{\Omega_r} + q}, \quad (6)$$

where $\Omega_{r \max}$, $M_{em \max}$ – critical absolute slip and torque; $q = 2 \cdot \frac{R_s}{R_r} \cdot \frac{\Omega_{r \max}}{\Omega + \Omega_r}$ – the coefficient of the stator active resistance.

After the transformation (Eq. (3)) the form is the following:

$$\Omega_r^2 - (2 \cdot k_m + k_m \cdot q - q) \cdot \Omega_r \cdot \Omega_{r \max} + \Omega_r^2 = 0, \quad (7)$$

where $\frac{M_{em \max}}{M_{em}} = k_m$ is stability margin of the asynchronous traction motor.

The absolute slip value is obtained by solving the equation Eq. (7) for the predetermined value k_m . Providing that $k_m > 1$ equation Eq. (6) has two real roots. The lowest of them corresponds to the work of the asynchronous traction motor within the ascending branch of the mechanical characteristics. This absolute slip value is maximum for a given stability margin value. The current value of the absolute slip that is determined by the formula Eq. (3), must not exceed this value. It is a condition for the steady work of the asynchronous traction motor.

The increasing voltage drop in the reactance of the stator and rotor is the reason for decrease of the stability margin with the speed increase of the asynchronous traction motor. Therefore, the performance of the asynchronous traction motor stability requires the reducing of the stator current value.

The asynchronous traction motor characteristics obtained with accepted principles of control were calculated taking into account the described approach. Figure 2 shows the dependence of the current value of the stator line voltage, the stator current and the electromagnetic torque on the rotor speed of the asynchronous traction motor that are obtained taking into account the above-mentioned restrictions and the importance of stability margin 1.1.

Figure 3 shows that the point A corresponds to the transition from the regulatory mode with the constant torque to the control mode with constant power (the boundary between the 1st and the 2nd zones of control). The point B shows the transition to voltage constraints of the stator and the engine limit under the continuous operation current and maximum current of the stator respectively (the transition between the 2nd and the 3rd control zone).

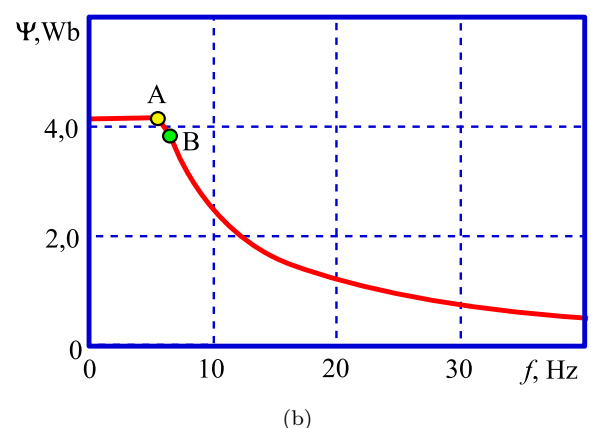
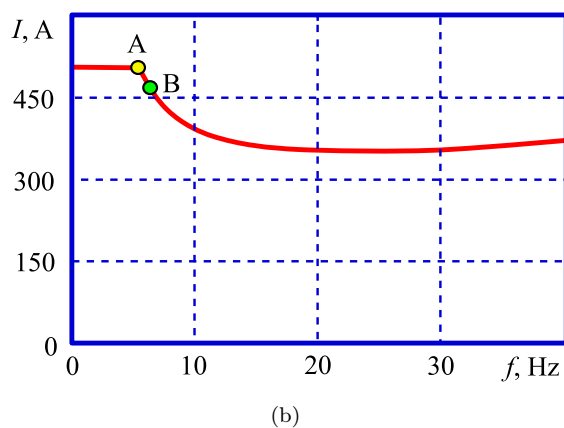
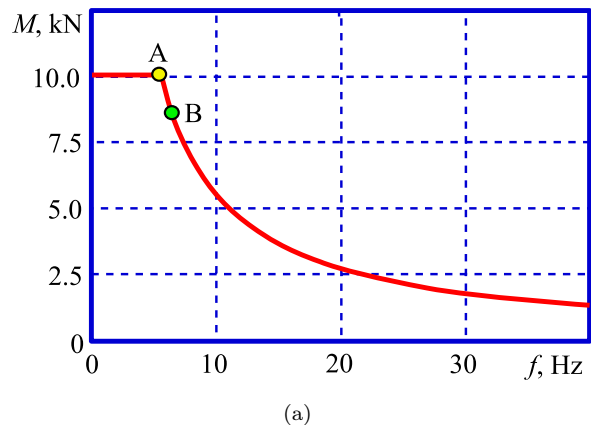
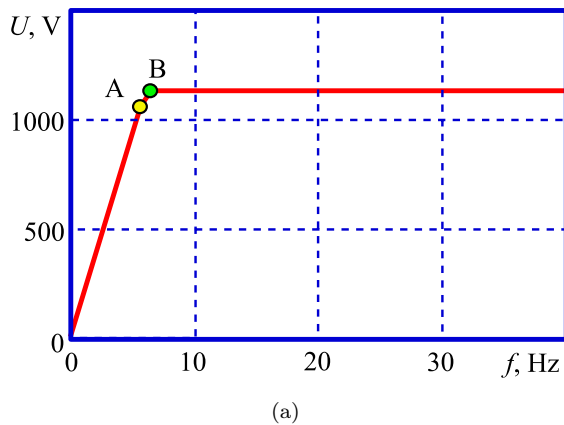


Fig. 2: The dependence of the stator line-to-line voltage (a) and stator phase current (b).

Fig. 3: The dependence of the electromagnetic torque (a) and rotor flux linkage (b).

The analysis of the obtained dependencies shows the achievement of the minimum stator current is possible with a slight weakening of the motor field in the constant power mode and with the voltage reserve. At the same time, the value of the stator current reduces in comparison with the 1st zone of regulation.

At first the electromagnetic shaft power increases due to the reduction of the reactive component of the stator current and then it reduces with the increasing speed and the decreasing rotor flux linkage. It is due to the voltage drop on the stator and rotor reactance increasing proportional to the rotor speed. As the rotor speed grows the influence of this effect increases. Also, stability margin reduces. When it reaches minimum allowed value, there is a need to reduce the stator current.

The described effects are particularly strong in the initial control positions because in this case the limit value of the stator voltage is much lower than the nominal value; and the voltage drop across the active and reactive resistances, depending on the current and speed of the rotation, are comparable to the motor EMF.

The increase of the stator current allows rising of the power of the asynchronous traction motor in the

case of a full field. The stator current increase gives effect only until the current stability limit when the motor operates in the field weakening mode. It is a consequence of the rapid increase in the voltage drop across the reactance of the stator and the rotor, which are defined by the increase of these resistances value and by high current.

5. Conclusion

Analysis of the results leads to the following conclusions. The asynchronous traction motor as a part of the traction electric locomotive works mainly in the field weakening mode, due to the need to obtain a fixed power from a diesel generator set. In the field-weakening area, it is necessary to the stability margin, as the maximum engine rotation speed is much higher than the rotation speed of the continuous mode.

The control of the asynchronous traction motor on the locomotive is carried out with three control zones. It is possible when the speed of the transition from the torque restriction to the power restriction is lower than the speed when the voltage limit of the diesel-

generator set is reached. In the 1st zone, the engine torque and rotor flux linkage are constant. In the 2nd zone, the locomotive power is constant. In the 3rd zone, the regulation is carried out with field weakening after reaching a voltage limit on the inverter output.

Stable operation of the asynchronous traction motor is possible, if the absolute slip does not exceed the value determined by the required stability margin. Its maintenance requires the reduction of the stator current. For the considered traction motor, that moment occurs when the rate of rotation is half or twice the nominal rate, depending on the stator current. Thus, the power of the asynchronous traction motor is determined by the steady work condition within the range of medium and high speeds.

Acknowledgment

The work was partly supported by Project SP2017/153 Research antenna systems, diagnostics and reliability of electric drives of the Student Grant System, VSB–Technical University of Ostrava.

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