The transfer function of a traction asynchronous motor controlled by a four-square converter

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Abstract. An expression for the transfer function of a traction asynchronous motor with a four-square converter is derived. It is shown that the basic properties of the traction motor, which are a four-square converter, correspond to the linearization coefficients. The values of linearization coefficients for a typical system in the entire region of equilibrium states are given.

1. Introduction

The effectiveness of functional diagnostics of electric equipment of the electric locomotive depends on how resolved the issue of the identification and refinement of the mathematical description of its electrical equipment, definitions of their input and output signals, the analysis of the results on parameters and signals using a priori information on the nominal values of the parameters of good installation and model defects [1].

When the diagnostics of the electric locomotive, usually assess the technical condition of certain electrical equipment, such as a subsystem for the conversion and distribution of input signals, hardware implementation of the input effects on the system, a subsystem of formation of control actions on the power converter subsystem of energy conversion and force generation of thrust and braking.

One of them methods of functional diagnostics is the use of estimates of the actual output diagnostic signals determined for each power equipment and, accordingly, reduced mathematically formulated by the transfer functions of traction equipment.

2. Main part

The four-square converter (FSC) 4qS find application for the automatic control of powerful traction asynchronous motors TAM [3]. For example, in figure 1 reduced the schematic diagram of the system of stabilization and control of the speed of rotation of the TAM, controlled by FSC 4qS.

The analysis of available literature materials showed that the issues of dynamics of automatic control of TAM by means of FSC 4qS are at the initial stage. This applies primarily to the study of the interrelated elements of TAM and FSC 4qS.

The paper is devoted to the question of dynamics, FSC 4qS is characterized by a force coefficient and a time constant, unchanged for all equilibrium states. A distinctive and characteristic mode of operation of FSC 4qS and TAM is that the system operates in both "traction" and "regenerative braking" mode and these parameters vary over a wide range [3].
There is also a question of linearization of the equations necessary for the study of the system in the "small", there is no expression of the transfer function in FSC 4qS and TAM, oriented for the purposes of functional diagnostics.

The aim of the proposed work is to fill the above gaps.

![Figure 1. Schematic diagram of the connections of the power transformer (PT), 4qS converter and asynchronous traction motor with short circuit diagnosis sensors and voltage diagnosis sensor.](image)

Given the connection scheme FSC 4qS and TAM, we find the relationship between the small deviations of the motor speed $\Delta \omega$ and the output voltage $\Delta U_{f}$, FSC 4qS.

To simplify, the following assumptions are made:

- neglect electrical transients in FSC 4qS and TAM;
- motor current and voltage at its terminals are sinusoidal;
- the output impedance of FSC 4qS at the fundamental frequency is defined as the ratio of the first harmonic of the voltage to the first harmonic of its current.

As it is known, the electromagnetic moment developed by electromagnetic forces on the rotor of an asynchronous machine is determined by the equality [4]

$$ M = \frac{P_{mx}}{\Omega}, $$

where $P_{mx}$ – mechanical power on the rotor, defined by the expression, $P_{mx} = mI^2r_2 \frac{1-s}{s}$; $\Omega$ - mechanical angular speed of the rotor.

We show $M$ through the applied phase voltage $U_{f1}$ - FSC 4qS, the parameters of the TAM and its slip. To do this, we will find through these values the current of the rotor winding $I_2$.

$$ I_2 = \frac{U_{f1}}{\left(r_1 + c_1 \frac{r_2}{s}\right)^2 + \left(x_{01} + c_1 x_{02}\right)^2}. $$

So:
\[ M = \frac{p m U_{mn}^2 r_s^2}{s} - \omega \left[ r_1 + c_1 \frac{r_s^2}{s} \right]^2 + \left( x_{01} + c_1 x_{02} \right)^2 \]  

(3)

For small deviations from the equilibrium state, the following equations are valid. The equation of motion of the drive consisting of electromagnetic and mechanical parts, the outcome of the linearized system is described [5].

\[ \Delta M_A - \Delta M_c = J p_m \omega, \]  

(4)

where \( M_A \) - the torque TAM, \( M_c \) - the moment of resistance of the actuating mechanism, \( p_m \) - the number of pairs of poles, \( \omega \) - the rotation speed; \( J \) - the total moment of inertia of the unit consisting of TAM, gearbox and wheelset, which is taken constant due to the large mass.

The equation for the deviation of engine torque in a small

\[ \Delta M_A = -k_A \Delta x - \beta_A \Delta \omega, \]  

(5)

de \( k_A \) - the torque TAM, \( \beta_A \) - the rigidity of the mechanical characteristics of the engine; \( k_A = -\frac{\partial M_A}{\partial x} \) - the coefficient sensitivity of the engine.

The effective value of the alternating current passing through the stator windings TAM is a function of the resistance \( \Delta x \) of the stator winding TAM and the speed of the motor \( \omega \).

\[ \Delta I = -k_A \Delta x - k_x \Delta \omega, \]  

(6)

where \( k_A = -\frac{\partial I}{\partial x} \)

\( k_x = -\frac{\partial I}{\partial \omega} \)

- the coefficient of relative specific change of current from frequency.

At the same time the reactance of the winding \( x \) is a function of the effective value of the current \( \Delta i_n \) in this winding and the current SFC 4qS \( \Delta I \):

\[ \Delta x = -k_x \Delta i_n - k_x' \Delta I, \]  

(7)

where \( k_x = -\frac{\partial x}{\partial i} \)

\( k_x' = \frac{\partial x}{\partial \omega} \)

Equation for SFC 4qS [3]

\[ \Delta U_{mn} = R_n \Delta i_n + R_c C pU_c - K_{m} \rho \Delta \omega \]  

(8)

where \( R_n \) - is the output active resistance of SFC 4qS, determined by the resistance of two thyristors in the open state \( R_{thy} = 0.13 - 0.17 \) Ohms; \( C \) - is the capacitance of the capacitor filter C; \( U \) - is the voltage on the capacitor filter; \( K_{m} = \frac{R_n T^*}{1 + k_x k_x'} \)

\( k_{m} = -\frac{\partial I}{\partial \omega} \)

\( k_x = -\frac{\partial I}{\partial x} \)

\( T \) - constant time dependent on both 4qS and TAM.
From equations (1), (2), (4) and (5) we have

$$ (\beta_0 + Jp_m) \Delta \omega = k_s \left( \Delta i_n - \frac{\Delta M_c}{k_s} \right) $$

(9)

where $k_s$ – the sensitivity coefficient given is equal to

$$ k_s = k_n - \frac{k_n}{1 + k'_n k_c} $$

(10)

$\beta_s$ – reduced stiffness of the mechanical characteristics of the engine

$$ \beta_s = \beta_n - \frac{k_n k_{\omega_n} k_n}{1 + k'_n k_c} $$

(11)

Equations (8), (9) corresponds to the block diagram of the TAM controlled SFC 4qS, shown in figure 2.

![Block diagram of TAM and SFC 4qS in "small".](image)

The block diagram of TAM and SFC 4qS corresponds to the transfer function

$$ \Delta \omega = \frac{k_{\omega_p} \Delta U_n - (1 + pT_n) \Delta M_c}{T_n Jp^2 + \left( \beta_s T_n + J - \frac{k_{\omega_p}}{R_n} K_\omega \right) p + \beta_s} $$

(12)

Diagram analysis in figure 2 and equation (12) shown that the TAM is characterized by an equivalent reduced sensitivity coefficient $k_s$ and a reduced equivalent stiffness mechanical characteristic $\beta_s$, determined by the formulas (10) and (11), and which are naturally different for the modes of “motion” and “regenerative braking”.

The reduced sensitivity coefficient $k_s$ (10) changes only in absolute value, and the reduced stiffness coefficient of the mechanical characteristic $\beta_s$ (11) changes both in absolute value and in sign, i.e. during the transition to regenerative braking [6].

The presence of flexible feedback, determined through the coefficient $K_\omega$, is explained by the fact that the effective value of the alternating current decreases with an increase in the rotation speed of the TAM.
Analysis of formulas (5), (6) and (8), and hence figure 1, figure 2 shown that the TAM coefficients $k_{\alpha}$, $\beta_\alpha$, $k_x$, $k_{\omega}$ and the 4qS coefficients $T_\alpha$, $k_x$, $K_{\omega}$ can also be used both separately and together as functional diagnostic features, and completely determine the initial dynamic properties of individual locomotive equipment and can be determined using the substitution scheme (figure 3).

![Figure 3. 4qS and TAM substitution scheme.](image)

In the scheme of substitution 4qS and TAM (figure 3) $x_1$ - reactive resistance 4qS; $x_2$ - reactive resistance of the stator dispersion; $x_m$ - reactive resistance of the magnetizing circuit of the motor; $x_3$ - reactive resistance of the rotor windings, led to the stator winding; $R_2$ - active resistance of the rotor, led to the stator winding; $r_1$ - active resistance of the stator winding; $c_1 = 1 + \frac{x_1}{x_m}$.

According to the diagram figure 3 for stator and rotor currents and torque.

$$I_1^2 = U^2 \left[ \frac{\left(x_1 + c_1 x'_1 + x_m\right)^2 s^2 + \left(r_1 s + c_1 R'_2\right)^2}{x(x_1 + x_1 + c_1 x'_2) + x_m\left(c_1 x_1 + c_1^2 x'_1\right)^2 s^2 + \left(r_1 s + c_1 R'_2\right)^2 \left(x + c_1 x_m\right)^2} \right]$$

$$I_2^2 = U^2 \frac{x_2 s^2}{x(x_1 + x_1 + c_1 x'_2) + x_m\left(c_1 x_1 + c_1^2 x'_1\right)^2 s^2 + \left(r_1 s + c_1 R'_2\right)^2 \left(x + c_1 x_m\right)^2}$$

$$M = \frac{m_1 I_2^2 R'_2}{s} c_1^2 / \omega_1$$

On the basis of (14) and (15), the sensitivity coefficient TAM, which is a diagnostic parameter, is defined as

$$k_{\alpha} = \frac{\partial M}{\partial x} = \frac{2\omega_1 M^2}{m_1 U^2 x^2 c_1^2 R'_2} \frac{\left(x + c_1 x_m\right)^2 \left(r_1 s + c_1 R'_2\right)^2 s^2}{s}$$

Another diagnostic parameter, as mentioned above, is the rigidity of the mechanical characteristic of the engine, the expression of which can be obtained from the derivative $\beta_\alpha = \left(\frac{\partial M}{\partial s}\right)_0$ using (14) and (15)

$$\beta_\alpha = M \frac{\omega_1}{\omega_1 s} \left[2 \frac{\omega_1 M}{m_1 c_1^2 x_1^2 R'_2 U^2} \left(\frac{\left(x + c_1 x_m\right)^2 \left(r_1 s + c_1 R'_2\right)^2}{s}\right) + S \left(x(x_1 + x_1 + c_1 x'_2) + x_m\left(c_1 x_1 + c_1^2 x'_1\right)^2 s^2\right) \right]$$

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Based on the analysis of known methods and purposes of diagnosis, types of diagnostic features, i.e. characteristics of the object used to determine its technical condition, used for functional diagnosis of electric locomotives, it is possible to control the parameters of electrical equipment, with the identification of the defect [7].

3. Conclusion
One of the possible methods of functional diagnosis of an electric locomotive, which is a complex dynamic object having a number of power traction electrical equipment, is a continuous monitoring of the current values of the transfer function coefficients and time constants and evaluation of their deviation from the nominal values. The given coefficients of the four-square converter $T_n$, $k_x$, $K_w$ working on the traction motor as well as the coefficient of sensitivity and rigidity of the mechanical characteristics of the traction motor controlled by the four-square converter can be used separately as the diagnosable signs and parameters of the electric locomotive.

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