Research and analysis of force and moment of the cascade asynchronous electric drives.

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Abstract. In the article, the research of force and the moment in the cascade asynchronous electric drives is provided and the analysis of the received decision is carried out. As an object of a research, the special types of electric drives with asynchronous motors possessing glad advantages in comparison with single-engine electric drives were selected. These are optimum mass-dimensional and energetic indices, the improved technological parameters allowing reaching big limits of regulation of rotational speed and the electromechanical moment, and the value of the moment can remain within rated value even in case of small rotational speeds or changes of the direction of movement. For optimum design of such types of electric drives and more exact and correct regulation and the researched parameters of force and the moment on a shaft of an electric drive, it is necessary to realize new approaches to a research and calculation. The carried-out analysis showed that the most optimum method of determination of force and the moment is the method based on electromechanical conversion of energy. The parameters received as a result of a research have necessary accuracy in comparison with the experimental data. The analysis of the conducted research shows that the received decision will allow improving quality, technical and economic indices of difficult technological processes of such industries as oil and gas branch, the heavy industry and mechanical engineering, a pulp-and-paper industry and others.

1. Introduction

Determination of force and the moment of the cascade asynchronous electric drives is the main difficulty. The specified method is computation of the electromagnetic energy which is saved up by the device in the considered time point. At the same time it is necessary to know the currents, the electromotive forces corresponding to them flux linkage in a rotor and the stator, phase angles of these values, and interposition of axes of a field of the stator and a rotor [1].

The carried-out analysis has shown that the most expedient method of definition of force and the moment is the method based on electromechanical transformation of energy, giving good coincidence of calculation with experimental data. And to define mechanical and electromechanical characteristics the conducted research is devoted to a solution of the problem of definition of force and the moment using electromechanical transformation of energy [2-4].
2. Solution of the task of determination of force and moment of the cascade asynchronous electric drives

We will consider a method of calculation of force and the moment in asynchronous electric drives and their components. It will allow defining mechanical characteristics of the electric drive. The moment equation for an idealized component is:

\[ M_{EM} = \frac{1}{2} i_a^2 \frac{dL_a}{dQ} + \frac{1}{2} i_x^2 \frac{dL_x}{dQ} + i_a i_x \frac{dL_{ax}}{dQ} \]  \hspace{1cm} (1)

where

- \( i_a \) – stator current;
- \( i_x \) – rotor current;
- \( L_a \) – inductance of the stator;
- \( L_x \) – inductance of a rotor;
- \( L_{ax} \) – inductance of the stator concerning a rotor;
- \( Q \) – angular provision of a mobile part (rotor).

In the asynchronous motor of the cascade electric drive, the electromechanical moment affects a rotor and the stator – opposite directional. Therefore we take the angle defining the provision of a rotor for an independent variable. Then the equation (1) will take a form:

\[ M_{EM} = \frac{1}{2} i_a^2 \frac{dL_a}{dQ_{rm}} + \frac{1}{2} i_x^2 \frac{dL_x}{dQ_{rm}} + i_a i_x \frac{dL_{ax}}{dQ_{rm}} \]  \hspace{1cm} (2)

where \( Q_{rm} \) – the corner defining the provision of a rotor.

Members of the equation (2) which enter own inductance of windings are equal to zero. This results from the fact that own inductance of any winding of an idealized component of the electric drive does not depend on the situation in an air gap, and coefficients of a self-induction do not depend on a spatial arrangement of a rotor. Then the equation (2) takes a form:

\[ M_{EM} = i_a i_x \frac{dL_{ax}}{dQ_{rm}}. \]  \hspace{1cm} (3)

That the moment on a shaft of the electric drive was not equal to zero, \( L_{ax} \) shall change in case of movement of a rotor. Quite the same situation occurs in the asynchronous motor of the cascade electric drive as one of windings is located on the stator, and another on a rotor. And windings are sine. Between sine windings there cannot be the inductive coupling, as well as creation of the moment, if the numbers of poles is different.

We will consider a case when on a rotor and the stator sinus windings of the \( n \) harmonious component of a winding of the stator \( a \) and a winding of a rotor \( x \) are present (figure 1). The corner \( Q_{rm} \), between axes of windings \( a \) and \( x \) also characterizes the provision of a rotor. If the corner size is positive, then a rotor moves counterclockwise.

The moment which is formed at interaction of two harmonious windings is:

\[ M_{EM} = i_a i_x \frac{dL_{ax}}{dQ_{rm}} = i_a i_x M_{ax} \frac{d}{dQ_{rm}} \left[ \cos (\phi + Q_p) \right] = -n p i_a i_x M_{ax} \sin n \delta \]  \hspace{1cm} (4)

The corner is equal in electric radians:

\[ Q = pQ_{rm} \]  \hspace{1cm} (5)
where \( p \) – number of couples of poles.

The mutual inductance of \( n \) harmonious windings is equal to:

\[
L_{\text{mut}} = M_{\text{mut}} \cos n(\phi + Q_r)
\]

where \( L_{\text{mut}} \) – mutual inductivity of windings;
\( M_{\text{mut}} \) – amplitude of cosine function;
\( \phi \) – an electrical angle between axes of windings.

Amplitude of the cosine function is equal to:

\[
M_{\text{mut}} = \frac{\mu_0 r l \pi N_{\text{st}} N_{\text{rot}}}{g}
\]

where \( r \) – radius of an air gap;
\( N_{\text{st}}, N_{\text{rot}} \) – amplitudes of winding functions of the stator and the rotor;
\( g \) – value of a gap;
\( l \) – axial length of a winding.

The angle of the moment is equal to:

\[
\delta_n = \phi + Q_r.
\]

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**Figure 1.** Ratio of spatial phases \( n \) of harmonicas of sinus windings.

1 – \( n \) harmonica of a winding x rotor;
2 – \( n \) stator of a winding harmonica.

The corner of the moment is various for each harmonica, as solid angles \( \phi_{\text{st}} \) and \( \phi_{\text{rot}} \) are various for the corresponding members of ranks of Fourier for windings. Thus, the formula (4) represents an
expression for the moment of an idealized component of an asynchronous cascade electric drive. We find the resultant moment summing of the harmonic moments. The moment received from interaction of sine windings depends on the number of couples of poles, currents in windings, the maximum value of mutual inductivity and a sine of the angle of the moment. The negative sign in a formula (4) shows that the moment aims to reduce an angle \( \delta_n \), to bring interacting windings into a situation when their axes match.

The conclusions stated above will allow defining quite precisely the created force and the developed moment on a shaft of the studied types of electric drives. For this purpose, it is necessary to define a ratio of spatial phases of harmonics of sinus windings, shift of vectors of axes of fields of the stator and a rotor and the electromagnetic energy reserved in the developed electric drive and its component. The two first tasks have been solved earlier; therefore it is necessary to define electromagnetic energy.

It is known that the energy concentrated in volume of the electromechanical device makes:

\[
W_{EM} = \frac{\Psi I}{2}. \tag{9}
\]

We will carry out transformation of a formula (9):

\[
W_{EM} = \frac{B^2}{2 \mu \mu_0} V \tag{10}
\]

where \( \Psi \) – flux linkage;

\( B \) – magnetic induction;

\( V \) – volume of an electromagnetic part;

\( \mu \) – magnetic permeability.

We will finally receive expression for energy [5]:

\[
W_{EM} = \frac{\delta l_m \tau}{\mu_0} \left( B_{snc}^2 + B_{snp}^2 - 2 B_{snc} B_{snp} \sin(\varphi_{se} - \varphi_{ce}) \right) \tag{11}
\]

where \( \delta \) – air gap;

\( l_m \) – length of an electromagnetic part of a component of the electric drive;

\( \tau \) – winding step;

\( B_{snc} \) – maximum magnetic induction of the stator;

\( B_{snp} \) – maximum magnetic induction of a rotor.

\( \varphi_{ce} \) – angle of shift of the field of the stator;

\( \varphi_{pe} \) – angle of shift of the field of a rotor.

Using the received conclusion for finding the reserved energy in a component of the electric drive and the technique stated below, it is possible to determine the size of instant force, the moment on a shaft and, as a result, mechanical characteristics of a component and the cascade electric drive in general. For this purpose the volume of the system is presented in the form of characteristic elementary volumes, for example, a tooth of the stator or a rotor. In each volume, energy is defined according to (10). All elementary values are summarized and, thereby, total electromagnetic energy of all device of time and for this spatial arrangement of a rotor concerning the stator is defined at present.

It is known that the effort developed by the electromechanical device makes:

\[
F = -\frac{\partial W_f}{\partial x} \tag{12}
\]
where \( W_f \) – electromagnetic energy reserved by the device;
\( x \) – coordinate of virtual movement.

As distribution of induction in a gap is based by means of the computer programs, which have been earlier developed by us, and there have been no analytical expressions, it is expedient to carry out numerical differentiation in expression (12). For this purpose, it is possible to apply the three-point template having sufficient accuracy [6]:

\[
F = -\frac{1}{2\Delta x} (-3W_{x-\Delta x} + 4W_x - W_{x+\Delta x}).
\]  
(13)

Calculations on a formula (13) can be made for any time point, i.e. for any angle of rotation of a rotor concerning the stator, considering that the size of energy is calculated at invariable flux linkage. Thereby we receive a value of force and the corresponding moment operating on a rotor throughout 360° turn of a rotor concerning the stator, i.e. instant value of force and the moment operating on a shaft of a component and the cascade electric drive. The received characteristics are shown in figures 2–4.

![Figure 2. Electromechanical characteristics of a component.](image1)

![Figure 3. Mechanical characteristics of a component.](image2)
3. Conclusion
The conducted research will allow defining quite precisely the force and the moment in asynchronous cascade electric actuators and also electromechanical and mechanical characteristics. By the example of the real asynchronous motor [7] and the model of an asynchronous cascade electric drive and its components, there were force, moment, electromechanical and mechanical characteristics. The discrepancy between calculated parameters and the real ones in the most difficult modes was made by no more than six percent. The received decision will allow constructing optimum mass-dimensional and energetic parameters of special asynchronous electric drives [8] for different industries [9-11].

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Figure 4. Mechanical characteristics of the cascade asynchronous electric drive.