

# Determination of power and moment on shaft of special asynchronous electric drives

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**Abstract.** In the article, questions and tasks of determination of power and the moment on a shaft of special asynchronous electric drives are considered. Use of special asynchronous electric drives in mechanical engineering and other industries is relevant. The considered types of electric drives possess the improved mass-dimensional indicators in comparison with single-engine systems. Also these types of electric drives have constructive advantages; the improved characteristics allow one to realize the technological process. But creation and design of new electric drives demands adjustment of existing or development of new methods and approaches of calculation of parameters. Determination of power and the moment on a shaft of special asynchronous electric drives is the main objective during design of electric drives. This task has been solved based on a method of electromechanical transformation of energy.

## 1. Introduction

Development of various industries demands creation of more technological and difficult equipment and mechanisms. In the heavy industry, improvement of systems of electric drives of machines and tools, electric transmissions of transport, electric drives of rolling mills is necessary. In pulp and paper industry, improvement of systems of electric drives of papermaking machines is required. In textile industry, improvement of systems of electric drives of weaving looms and big sewing machines is necessary. Such modernization will allow one to improve quality, technical and economic indicators of the technological process.

Use of special asynchronous electric drives [1, 2] will allow one to solve a problem of modernization of the equipment and mechanisms. The considered types of electric drives possess the improved mass-dimensional characteristics and power indicators. New mathematical models of the specified devices are necessary for creation of special asynchronous electric drives and solving optimizing tasks. Key parameters which are determined by the mathematical model are expressions for determination of power and the moment of the electric motor [3, 4]. Quite often the solution of such tasks requires numerical methods of calculation [5, 6]. The analytical solution of a problem of definition of the moment and the power removed from a shaft of special asynchronous electric drives is given below.

## 2. Derivation of formulas for determining power and moment

Derivation of formulas for definition of the moment and the power removed from a shaft of the axial asynchronous engine with a short-circuited rotor is given below.

The moment operating on a rotor [3] is:



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$$M = - \frac{\partial W_f}{\partial x} \left( \Psi = const \right) \quad (1)$$

where  $W_f$  – electromagnetic energy;

$x$  – movement of a rotor relatively the static position.

Energy of the electromagnetic energy will be equal to the linear integral along the way of integration convenient to us [3]:

$$W_f = \int_0^{\Psi_{1'}, \Psi_{2'}} \left( i_1 d\tilde{\Psi}_{1'} + i_2 d\tilde{\Psi}_{2'} \right), \quad (2)$$

where  $\Psi_{1'}, \Psi_{2'}$  – flux linkage from a winding of the stator and a winding of a rotor;

$i_1, i_2$  – electric currents in windings of the stator and a rotor;

$\tilde{\Psi}_{1'}, \tilde{\Psi}_{2'}$  – flux linkage, characterizing ways of integration.

The definition of a ratio between electric currents and flux linkage depends on geometrical parameters of magnetic systems of components of special asynchronous electric drives. Having the geometrical sizes, the equations on the basis of laws for a magnetic chain are worked out. Each specific objective is solved separately as distribution of the electromagnetic field depends on the number of couples of poles, a type of a winding of the stator and the rotor, a design of the magnetic system. Asynchronous engines of both cylindrical and axial designs with a short-circuited rotor with four couples of poles have been considered. A stator winding is two-layer with a step equal to nine, with the number of grooves on the stator equal to thirty-six. The number of grooves on the rotor is twenty-six. For this example, distribution of the magnetic field created by a winding of the stator and the field of a rotor has been constructed.

The magnetic field of the stator is symmetric and consists of four poles. The distributed three-phase winding of the stator in the form of an equivalent winding. The equivalent winding consists of two concentrated coils with the identical number of rounds. Four poles similar to a real winding are formed as a result. Let us consider that via the equivalent coil, the current, created in the same magnetic field, as well as in real winding, proceeds.

The magnetic field of the rotor is symmetric and consists of four poles. Let us make an equivalent of a short-circuited winding of the rotor on four windings, which exist on one round. On these windings, equivalent current  $i_{2\phi}$ , creating the same magnetic field as a real winding, proceeds.

For the magnetic system of the studied components of special electric drives, let us make the equivalent circuit.

Let us accept that the magnetic resistance of a yoke of the stator and magnetic resistance of its teeth is equal to zero. Then magnetic resistance of gaps under four teeth  $R_{1M}$  is equal as system symmetric. At the same time, magnetic resistance of four identical parts of the magnetic conductor of rotor  $R_{2M}$ , equal among themselves, is not equal to zero. Magnetic streams  $\Phi_1$ , passing through teeth with coils and through teeth without coils of the magnetic conductor of the stator, are equal. Also magnetic streams  $\Phi_2$ , passing through a rotor magnetic conductor, are also equal.

On the basis of laws for a magnetic chain, let us write down the following system of the equations:

$$\begin{cases} 2\Phi_{1M1}R_{1M1} + \Phi_{2M2}R_{2M2} = i_{1\vartheta}w_{1\vartheta} + i_{2\vartheta}w_{2\vartheta}; \\ \Phi_1 = 2\Phi_2; \end{cases} \quad (3)$$

Solving system (3), it is possible to receive dependences:

$$\begin{cases} i_{1\vartheta} = 2\frac{\Psi}{w_{1\vartheta}^2}R_{1M1} + \frac{\Psi}{2w_{1\vartheta}^2}R_{2M2} - i_{2\vartheta}\frac{w_{2\vartheta}}{w_{1\vartheta}}; \\ i_{2\vartheta} = 4\frac{\Psi}{w_{2\vartheta}^2}R_{1M1} + \frac{\Psi}{2w_{2\vartheta}^2}R_{2M2} - i_{1\vartheta}\frac{w_{1\vartheta}}{w_{2\vartheta}}, \end{cases} \quad (4)$$

Let us substitute (4) in (2):

$$\begin{aligned} W_f = & \int_0^{\Psi_1, \Psi_2} \left( i_{1\vartheta} d\tilde{\Psi}_1 + i_{2\vartheta} d\tilde{\Psi}_2 \right) = \int_0^{\Psi_1, \Psi_2} \left( 2\frac{\Psi}{w_{1\vartheta}^2}R_{1M1} + \frac{\Psi}{2w_{1\vartheta}^2}R_{2M2} - i_{2\vartheta}\frac{w_{2\vartheta}}{w_{1\vartheta}} \right) d\Psi_1 + \\ & + \int_0^{\Psi_1, \Psi_2} \left( 4\frac{\Psi}{w_{2\vartheta}^2}R_{1M1} + \frac{\Psi}{2w_{2\vartheta}^2}R_{2M2} - i_{1\vartheta}\frac{w_{1\vartheta}}{w_{2\vartheta}} \right) d\Psi_2 = \frac{\Phi^2}{2}R_{1M1} + \frac{\Phi^2}{2}R_{2M2} + \\ & + \frac{w_{1\vartheta}}{w_{2\vartheta}} \int_0^{\Psi_1, \Psi_2} i_{1\vartheta} d\Psi_2, \end{aligned} \quad (5)$$

where  $\Psi_1, \Psi_2$  – the flux linkage created by a winding of the stator and the rotor.

In comparison with other composed formulas (5), such component as  $\frac{w_{1\vartheta}}{w_{2\vartheta}} \int_0^{\Psi_1, \Psi_2} i_{1\vartheta} d\Psi_2$  is

considerably small and, therefore, does not influence the size of energy of magnetic field. Then it is possible to write down (5) as follows:

$$W_{f1} = \frac{\Phi^2}{2}R_{1M1} + \frac{\Phi^2}{2}R_{2M2}, \quad (6)$$

For receiving the expression of the moment, let us differentiate (6) on movement  $\theta$ . Turning angle  $\theta$  is a possible angle of rotation of fields of the stator and the rotor relatively each other. As only  $R_{1M}$  and  $R_{2M}$  depend on  $\theta$ , then let us write down the expression for the moment:

$$M = - \frac{\partial W}{\partial \theta} \bigg|_{\Psi = \text{const}},$$

or

$$M = - \frac{\Phi^2}{2} * \frac{dR}{d\theta} - \frac{\Phi^2}{2} * \frac{dR}{d\theta}. \quad (7)$$

For receiving a final expression for the moment, let us express magnetic resistance through  $\theta$ .  
Magnetic resistance of a gap [3] is:

$$R_{M1} = \frac{\delta}{\mu_0 S}. \quad (8)$$

where  $\delta$  – size of an air gap;

$S$  – the area blocked by a part of a magnetic conductor of a rotor, limited to certain corner  $\theta$ , which changes as a result of rotation of the rotor;

$\mu_0$  – magnetic permeability of air.

The area blocked by a part of a ring of a magnetic conductor of the rotor:

$$S = \frac{1}{2} \left( r_{ext}^2 - r_{int}^2 \right). \quad (9)$$

where  $r_{ext}, r_{int}$  – external and internal radiuses of components.

Let us substitute expression (9) in (8):

$$R_{M1} = \frac{2\delta}{\mu_0 \left( r_{ext}^2 - r_{int}^2 \right)} * \frac{1}{\theta}. \quad (10)$$

Magnetic resistance of a half of a ring of the rotor [3] is:

$$R_{M2} = \frac{l_{half}}{\mu_a S_1}. \quad (11)$$

where  $l_{half}$  – length of a half of the rotor;

$S_1$  – cross-sectional area of a half of the rotor;

$\mu_a$  – magnetic permeability of steel.

The cross-sectional area of a half of the rotor:

$$S_1 = a \left( r_{ext} - r_{int} \right). \quad (12)$$

The length of a half of the rotor:

$$l_{half} = r_{midle} \theta = \frac{r_{ext} + r_{int}}{2} \theta. \quad (13)$$

Let us substitute expressions (12) and (13) in (11):

$$R_{M2} = \frac{r_{ext} + r_{int}}{2\mu_a \left( r_{ext} - r_{int} \right) a} * \theta. \quad (14)$$

Let us calculate derivatives from (10) and (14) on  $\theta$ :

$$\frac{dR_{M1}}{d\theta} = - \frac{2\delta}{\mu_0 \left( r_{ext}^2 - r_{int}^2 \right) \theta^2}. \quad (15)$$

$$\frac{dR_{M2}}{d\theta} = \frac{r_{ext} + r_{int}}{2\mu_a \left( r_{ext} - r_{int} \right) a}. \quad (16)$$

Let us place the received derivatives in equations (7), (15) and (16):

$$M = \frac{\Phi^2}{2} * \frac{2\delta}{\mu_0 \left( r_{ext}^2 - r_{int}^2 \right)} - \frac{\Phi^2}{2} * \frac{r_{ext} + r_{int}}{2\mu_a \left( r_{ext} - r_{int} \right) a}. \quad (17)$$

Let us define the magnetic streams created by the stator and the rotor windings as follows [3, 4]:

$$\Phi_1 = B_\delta S = B_\delta \frac{r_{ext}^2 - r_{int}^2}{2} * \theta. \quad (18)$$

$$\Phi_2 = B_{mc} S_1 = B_{mc} \left( r_{ext} - r_{int} \right) a. \quad (19)$$

where  $B_g, B_{mc}$  – magnetic induction of a gap and the magnetic conductor.

An average radius is determined by a formula:

$$r_{midle} = \frac{r_{ext} + r_{int}}{2}. \quad (20)$$

Let us introduce a new parameter:

$$d = r_{ext} - r_{int}. \quad (21)$$

Then it is possible to receive finally the expression for the moment operating on the rotor, having substituted in (17) equations (18) and (19), as well as (20) and (21):

$$M = \frac{B_g^2 r_{midle} d \delta}{2\mu_0} - \frac{B_{mc}^2 dr_{midle} a}{2\mu_a}. \quad (22)$$

The full mechanical capacity developed on the rotor [4] is:

$$P_{MX} = 2\pi n_1 (1-s) M. \quad (23)$$

where  $n_1$  – frequency of rotation of the field of the stator;

$s$  – size of sliding of the rotor.

The power removed from the shaft is:

$$\frac{P}{2} = k_{MX,A} P_{MX}. \quad (24)$$

where  $k_{MX,A}$  – the coefficient considering mechanical and additional losses.

Substituting (23) in (24), one will receive the following formula:

$$\frac{P}{2} = k_{MX,A} 2\pi n_1 (1-s) M. \quad (25)$$

Let us introduce a variable in the formula:

$$s_1 = 1 - s \quad (26)$$

Expression (25) taking into account (26) takes a form:

$$P_2 = k_{MX,A} \frac{2\pi n s M}{1} \quad (27)$$

The final expression for the power removed from the shaft is:

$$P_2 = \frac{\pi n k}{\mu_0} \frac{1}{MX,A} \frac{s}{1} B_{\delta}^2 r_{middle} d\delta - \frac{\pi n k}{\mu_a} \frac{1}{MX,A} \frac{s}{1} B_{mc}^2 r_{middle} da \quad (28)$$

Received dependences (22) and (28) are used for determination of the power and the moment removed from the shaft of special asynchronous electric drives.

### 3. Conclusion

In the article, the problem of determination of power and the moment on a shaft of special asynchronous electric drives has been solved. The use of special asynchronous electric drives will allow creating the equipment and mechanisms [7, 8] with the improved mass-dimensional and power indicators in comparison with single-engine systems. Creation of such types of drives and receiving characteristics of production control determination of power and the moment [9, 10] on a shaft of electric drives are necessary.

On the basis of the method of electromechanical transformation of energy [11], this task has been solved. This decision can be used in solving problems of creation of optimum types of electric drives [12, 13] and their components. By the example of the quadripolar asynchronous electric motor with a short-circuited winding of the rotor, the objective has been solved. The type of a winding of the stator does not influence a power equation conclusion. The created field of windings consists of the identical number of the symmetric parts equal to the number of poles. Depending on the number of poles, the number of the equations in system (3) will change. A further conclusion of the equations will be analogous.

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