Special synchronous motors for driving reclamation pumps

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Abstract. Possibilities of contactless excitation of a synchronous motor of a special design intended for driving pumps in irrigated agriculture are considered. The possibility of using an asynchronous machine with a contactless exciter is considered. An asynchronous machine with a rotating semiconductor unregulated rectifier is installed on the common shaft of the main machine (motor) and exciter.

1. Introduction
Agricultural production is a major consumer of electric pumps and electrical pumping equipment. The irrigated agriculture industry requires a lot of pumps. Electric pumps consume a significant amount of electricity, which has a significant impact on the economic performance of the industry. Synchronous motors are widely used in pump drives due to the highest energy indicators among electrical machines (efficiency and cosφ). The limiting factors for the use of these motors are their higher cost and complexity of operation compared to asynchronous squirrel-cage motors. In recent years attempts have been made to simplify engine design and reduce operating costs. Among the most successful technical solutions in this area there are synchronous motors with a double armature winding (DAWSM) designed by Kuban State Agrarian University [1-2].

Simplification of the motor is achieved by expanding the functions of the stator (armature) winding, which combines the traditional functions of converting energy from electrical to mechanical and automatic excitation control (AEC) of the motor. Such combination becomes possible when a...
three-phase winding is made in the form of two parallel branches, one of which (reference) is wye-connected (Fig. 1), and the other is connected as through-type in series with a rectifier VD1-VD6 and an excitation winding (EW). The AEC principle is realised by changing the current of three-phase windings when the motor load and/or voltage at its terminals changes. In this case the excitation regulation principle is determined by the parameters of all three windings.

2. Materials and methods

The use of a double armature winding allows solving other important problems of synchronous electric drives. The starting current is reduced four times during asynchronous starting, if both stator windings are connected in series, and the excitation winding is connected to the discharge resistance.

Parallel branches of a three-phase winding may be identical, as is the case with a traditional winding with two parallel branches. In this case, DAWSM is connected to a power source (network) through a special transformer T (Figure 2), which provides a voltage on the through-type winding, increased by 5-10% in relation to the reference winding. Such motor circuit is convenient when using transformer-motor units, in particular, in mobile installations connected to a 10 kV network at a motor voltage below 1 kV.

![Figure 2. Unit "transformer-DAWSM"](image_url)

The circuits presented in Figures 1 and 2 show that the brush-contact unit is retained in the motor design for transmitting current to the rotating excitation winding of synchronous motors. The problem of contactless excitation of the DAWSM can be solved by using an asynchronous exciter (AE) based on a traditional asynchronous machine with a wound rotor. The primary stationary winding of the asynchronous exciter is connected in series with the through-type stator winding of the DAWSM (Figure 3), and the secondary one, located on the common shaft with the DAWSM, is connected in series with the rectifier and the excitation winding of the DAWSM, providing contactless transmission of driving power. The parameters of the contactless exciter must be consistent with the parameters of the main windings of the DAWSM and provide AEC according to a given control principle.
3. The mathematical description

The mathematical description of a contactless exciter as part of a machine-valve complex of a synchronous motor can be performed in various coordinate systems and with varying degrees of detailing of constant and variable parameters. So, in [4], to describe various options for brushless excitation devices, the description of the electrical circuits of the exciter and electromechanical processes in phase coordinates and in various systems of transformed coordinates is used. In this case, the order of the system of equations for describing the exciter is comparable, and sometimes even higher than that of the main machine, which is not quite acceptable for describing a contactless DAWSM (CDAWSM), which already has a complex mathematical description. In those cases where the exciter is a dependent object of study, its mathematical description can be based on simplifying approaches, in particular, on the use of equivalent circuits in phase coordinates and their transformation together with the conjugate elements of the machine-valve system.

In [5], the possibility of describing electromechanical and electromagnetic processes in an exciter in various coordinate systems, including the coordinates of a generalized eigenvector, is considered. One of the disadvantages of this method is the complexity of the mathematical model of the machine complex, since the exciter, which is an auxiliary machine, is described in the same complex way as the main synchronous machine. With regard to CDAWSM, the search for ways to simplify the mathematical description of the exciter and the approximation of the CDAWSM model to the basic version of the machine is relevant.

Sufficient accuracy of the mathematical description of AE is provided by traditional T- and L-shaped equivalent circuits of an asynchronous machine in phase coordinates. The active resistance of the AE rotor circuit changes in transient electromechanical processes associated with a change in the instantaneous value of the load angle, and remains constant in static modes of operation.

The reduction of the parameters of the AE rotor circuit to the AE stator winding is carried out with allowance for the reduction coefficients of currents $m_a$, voltages $m_v$, and resistances $m_u$, which takes into account possible mismatches in the number of phases of the stator and rotor circuits and the winding coefficients of the stator and rotor windings.

According to [6]:

Figure 3. Contactless DAWSM with an asynchronous exciter
\[ m_1 = m_1 W_{st} k_{wc1} / (m_2 W_{rot} k_{wc2}), \]
\[ W_{st}, W_{rot} - number of turns of the stator and rotor windings connected in series; \]
\[ k_{wc1}, k_{wc2} - winding coefficients of the AE stator and rotor windings: \]
\[ m_a = m_2 m_r / m_1, \]
\[ m_c = m_a m_r. \]

Otherwise, the reduction of the parameters of the rotor circuit to the stator one does not differ from the analogous operation for the DAWSM with a rotating transformer.

The ratio of the instantaneous slip values of the synchronous motor (SM) and AE will be established based on the equality of the rotors speed and the current frequency in the stator windings of the SM and AE.

Synchronous motor slip:
\[ S_s = (n_{1s} - n_2) / n_{1s}, \]
where \( n_{1s} \) – field rotation frequency of the SM; \( n_2 \) – rotor speed.

Accordingly, the AE slip:
\[ S_a = (n_{1a} - n_2) / n_{1a}, \]
where the index "a" means belonging to AE.

In formula (2), with the coinciding directions of SM and AE field rotation, \( n_{1s} \) and \( n_{1a} \) have positive values; for the opposite, \( n_{1a} \) is negative.

The joint solution of equations (1) and (2) with respect to slip \( s_a \) gives:
\[ s_a = 1 - \frac{n_{1s} + n_{1s} \cdot s_s}{n_{1a}}. \]

The equation can be represented in the transformed form:
\[ s_a = 1 - \frac{p_a (1 - s_s)}{p_s}, \]
where \( p_a, p_s \) are the numbers of pole pairs of AE and SM, respectively.

As in the case of a rotating transformer, in approximate calculations the magnetization branch of AE can be neglected. In this case, the equivalent resistance of the field unit has the form:
\[ r_e = r_{1a} + (r_e + r_{2a}) / s_{1a}; \]
\[ x_e = x_{1a} + x_{2a} \cdot s_{1a}. \]

If it is necessary to increase the accuracy of calculations by taking into account the parameters of the magnetization branch, the equations of equivalent resistances should be determined by the complex equations of the T- or L-shaped equivalent circuit. So, for a T-shaped equivalent circuit, we have:
\[ Z_e = Z_{1a} + (Z_{2a} + Z_e) Z_{ema} / (Z_{ema} + Z_e + Z_{2a}), \]
where \( Z_{1a} = r_{1a} + jx_{1a}, \]
\[ Z_{2a} = r_{2a} / s_{1a} + jx_{2a}; \]
\[ Z_e = r_e / s_{1a} + jx_e; \]
\[ Z_{ema} = r_m + jx_m. \]

It is assumed in the equations that:
\[ r_e = Re(Z_e); \quad x_e = Im(Z_e). \]

As a result of these transformations, we obtain a design diagram of the CDAWSM circuit with AE, similar to the base motor of the contact design, but with its own values for \( r_e \) and \( x_e \). To study the symmetric modes in the DAWSM with AE, the equations of the DAWSM mathematical model describing electromechanical processes in the SM and the electromagnetic processes in the electrical circuits of the machine can also be used.

As for the electromagnetic torque of AE, which in the nominal load mode is only 2-7 (in some cases up to 20) percent of the torque of the SM, the traditional approach of the general theory of electrical machines, based on the analysis of the energy diagram of an asynchronous machine, can be used to determine it. To implement this method, well-known relationships can be used [3]:
\[ M_{ema} = P_{ema} W_{1a}, \]
where \( M_{ema} \) - electromagnetic torque; \( P_{ema} \) - electromagnetic power and \( W_{1a} \) - angular field rotation frequency of AE:
\[ M_{ema} = m_1 (L_2')^2 (r_2' + r_e') / s_{1a}. \]
The joint solution of equations (3) and (4) gives:

\[ M_{ema} = m_1 (I_1')^2 \frac{r_s' + r_e'}{2\pi \cdot f_1 (\frac{1}{p_a} - \frac{1 - s_s}{p_s})}. \]

If we neglect the magnetizing branch of AE, the current \( I_2' \) becomes equal to the stator current of AE (the current in the through-type winding of the SM). Taking into account that \( I_2'^2 = I_{d2}^2 + I_{q2}^2 \), we can finally write:

\[ M_{ema} = \frac{3}{2} \frac{(I_{d2}^2 + I_{q2}^2)(r_2' + r_e')}{\pi \cdot f_1 (\frac{1}{p_a} - \frac{1 - s_s}{p_s})}. \]

where \( p_a \) is a positive integer with the concordant rotation of the magnetic fields of SM and AE, and when using AE in the opposite connection it should be used with a minus sign. Accordingly, the electromagnetic torque of AE has a positive or negative value in the steady state mode. The equation of rotor motion in this case takes the form:

\[ H \frac{d\omega}{dt} = \psi_d 1' \cdot q_1 - \psi_q 1' \cdot d_1 + \psi_d 2' \cdot q_2 - \psi_q 2' \cdot d_2 + \frac{3}{2} \frac{(I_{d2}^2 + I_{q2}^2)(r_2' + r_e')}{\pi \cdot f_1 (\frac{1}{p_a} - \frac{1 - s_s}{p_s})} \cdot m_r. \]

The presented equations of the contactless DAWSM with AE can be used to analyze the processes in the windings (electrical circuits) of a synchronous motor as the main machine, but do not reflect in detail the electromagnetic processes in AE. If it is necessary to carry out such studies, the method of mathematical description of AE based on the energy conservation law and the virtual displacement principle can be used [6].

The flux linkage of the stator and rotor windings of AE, expressed in terms of inductions and currents, in phase coordinates has the form:

\[ \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \\ \psi_x \\ \psi_y \\ \psi_z \end{bmatrix} = \begin{bmatrix} L_{a} & \frac{1}{2}L_{ab} & L_{ac} & L_{ax} & L_{ay} & L_{az} \\ \frac{1}{2}L_{ab} & L_{b} & L_{bc} & L_{bx} & L_{by} & L_{bz} \\ L_{ac} & L_{bc} & L_{c} & L_{cx} & L_{cy} & L_{cz} \\ L_{ax} & L_{bx} & L_{cx} & L_{x} & L_{xy} & L_{xz} \\ L_{ay} & L_{by} & L_{cy} & L_{xy} & L_{y} & L_{yz} \\ L_{az} & L_{bz} & L_{cz} & L_{xz} & L_{yz} & L_{z} \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_x \\ i_y \\ i_z \end{bmatrix}. \]

For a symmetrical asynchronous machine \( L_a = L_b = L_c; L_x = L_y = L_z; L_{ab} = L_{bc} = =L_{ac}; L_{ay} = L_{az} = L_{cz} = L_{xz}. \)

Coefficients of mutual induction between the stator and rotor windings of AE are the functions of their relative position angle \( \gamma_a \). When expanding in a Fourier series in the angle \( \gamma_a \) and neglecting the higher harmonics of the series, these coefficients can be written in the form:

\[ \begin{align*}
L_{ax} &= L_{by} = L_{cz} = m_{xya} \cos \gamma_a; \\
L_{ay} &= L_{dx} = L_{cx} = m_{xya} \cos(\gamma_a - 2\pi/3); \\
L_{az} &= L_{bx} = L_{cy} = m_{xya} \cos(\gamma_a + 2\pi/3). 
\end{align*} \]

The electromagnetic torque, expressed in terms of flux linkages and currents, can be written by the equation:

\[ M_a = -\frac{H}{p_m} \frac{d^2 \gamma}{dt^2} \delta (\psi_a i_{a2} + \psi_b i_{b2} + \psi_c i_{c2} + \psi_x i_x + \psi_y i_y + \psi_z i_z). \]
Together with the equations of the mathematical description of DAWSM, they describe the electromagnetic process in the considered machine-valve system.

4. Conclusion
The use of a contactless DAWSM with AE allows one to solve effectively a number of auxiliary tasks of the electric drive of pumps and other mechanisms. These are setting up a mechanical system after transportation or after long (seasonal) storage, starting without load using the exciter as a barring engine. That provides a significant decrease in starting current with acceptable starting characteristics. The features of the mathematical description of the CDAWSM are considered when representing AE by a simplified equivalent circuit and when describing AE in rotating orthogonal coordinates.

References

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