Technical data and results of simulation of a prototype of a biphase compensated asynchronous motor, on whose stator the development of which is justified is described. A mathematical model of a biphase low-speed compensated asynchronous motor is developed. A model is based on the Kirchhoff's equation for two network windings and two compensator stator windings. A sequence of solution of the equations and calculation of a vector magnetic potential and performance characteristics of a biphase low-speed compensated asynchronous motor is described. Technical data and results of simulation of a prototype of a biphase compensated asynchronous motor, on whose stator the winding is located, are presented. Its currents excite 10 pairs of poles. An analysis of obtained results confirms the possibility and expedience of development and mass implementation in the oil industry of highly economical energy efficient biphase compensated low-speed asynchronous motors.
**Introduction**

Mechanical and electrical equipment that is used to lift oil to the surface is determined largely by flow rate of wells [1]. Wells with high and mean oil rates are operated by centrifugal pumps with electric drive from submersible induction motors. Frequency of rotation of a circular magnetic field of such motors, which is excited by currents of three-phase stator winding is usually 3000 min⁻¹ [2]. The shaft torque of submerged induction motors, developed by electromagnetic forces, depends on the area of the outer surface of the electric motor rotor. Due to the small rotor diameter of submerged asynchronous motors, the torque required for operation of the centrifugal pump is provided by selection of appropriate rotor length and the motor as a whole.

Operation of low-productivity wells with rate of not more than 5 m³ per day is performed by rod pump systems (RPS). Reciprocating motion of a plunger of plunger pumps RPS in most of the cases is carried out using three-phase asynchronous electric motors with an higher starting torque or with higher slip [3, 4]. On a practical level, asynchronous electric motors with nominal power of 15, 22, 30 kW with rotational frequency of a stator magnetic field of 750, 1000, 1500 min⁻¹ are most used [5]. V-belt drive is used to transmit the torque from an electric motor shaft to a reductor input shaft. Depending on the diameter of a motor shaft pulley V-belt drive changes rotational speed in 2.86-4.5 times. In case reductor gear ratio is 40 then mentioned asynchronous motors ensure the operation of RPS with a number of double strokes of a plunger equal to 4-12.5 per minute. Having such frequency of double strokes of a plunder and low well production, periods of its shutdown, when liquid accumulates. Such mode of operation of RPS are called cyclic in technical literature and characterized by a number of significant drawbacks, which are indicated in works [6-8]. Transition to the most optimal “continuous” operation mode of RPS that lift liquid from wells with low production rate consider installation of asynchronous electric motors with rotational speed of a magnetic field of 375, 200, 150 min⁻¹ at pumpjacks [9-11].

Among the primary problems that arise during the development of low-speed electromechanical energy converters, it is necessary to distinguish two such as need to reduce overall dimensions of engines and increase a values of their most important energy index which is power coefficient [12-14].

Let us focus on possible approaches to solve the problems mentioned above.

**New direction in improvement of RPS electric drive**

It is known from the theory of electric alternating current machines that the rotational speed of the stator magnetic field of the stator of asynchronous electric motors $n_0$, frequency of voltage in a supply network $f$ and a number of pole pairs of a stator winding $p$ are connected to each other by the equation [15-17]

$$n_0 = 60 f / p. \tag{1}$$

It is obvious that frequency of rotational speed of a magnetic field of the stator at 50 Hz of supply voltage is clearly determined by the number of pole pairs of its winding.

Dependence of rotational speed of a circular magnetic field on a number of pairs of poles of a stator winding

<table>
<thead>
<tr>
<th>$n_0$, min⁻¹</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3000</td>
<td>1500</td>
<td>1000</td>
<td>750</td>
<td>500</td>
<td>375</td>
<td>300</td>
<td>200</td>
<td>150</td>
</tr>
</tbody>
</table>

According to the data presented, development of asynchronous electric motors with a magnetic field of rotation frequency of 300, 200, 150 min⁻¹ considers the placement of the three-phase winding with a number of pairs of poles of 10, 15, 20 in stator grooves respectively.

The diameter of internal stator boring depends on a number of pairs of poles of the three-phase stator winding

$$d_s = 2 p \tau / \pi, \tag{2}$$

where $\tau$ is for length of pole division. As a number of pairs of poles of the three-phase winding increases, a diameter of the stator inner boring and outer stator diameter increase. An outer rotor diameter increases as well. That diameter is less than a diameter of the inner stator boring by double amount of air gap accepted for small and medium power engines 0.35-0.70 mm [18]. Consequently, dimensions of a motor increase as a number of pairs of poles of the stator winding increases and rotation frequency of its magnetic field decreases. Increase in a rotor diameter, caused by increase in a number of pairs of poles of the stator winding, leads to increase in the flywheel moment of a rotor and negatively affects the speed of an engine and dynamics of a plunger motor drive.
One of the solutions contributing to reduce in overall dimensions of asynchronous motors of an electric drive of the plunger RPS and increase in their speed is to place a two-phase winding in the stator grooves. Such a technical solution allows to reduce the length of the pole division of a stator winding in 1.5 times, which helps to reduce an inner stator diameter and outer rotor diameter.

However, until recently asynchronous electric motors with a two-phase winding on a stator have not been considered as an alternative to asynchronous electric motors with a three-phase winding. That was explained by poor performance characteristics of two-phase asynchronous motors and their more complicated design. The first disadvantage of asynchronous electric motors with a two-phase winding on a stator is caused by two factors such as ellipse shape of a magnetic field existing in an air gap and by using of a phase-shifting element in an engine design [19–21].

Development of the original design of a two-phase asynchronous electric motor [22] changes the situation dramatically.

There are two equal groups of sections in the grooves of the steel laminated core of the stator of such a motor. Sections are made from isolated wire, usually copper. Sections of one group differ from sections of another group by a number of turns and wire cross-section. Stacking of sections of groups in grooves and their connection schemes in the formation of single-phase windings are carried out in a special way to ensure spatial shift of axes of windings by 90°. Outputs of single-phase winding formed by sections that have a smaller number of turns are connected to one of the phase voltages of a four-wire three-phase supply network. Outputs of a single-phase winding formed by sections with a large number of turns are connected to the phase-to-phase voltage of the supply network, which varies in time with a phase shift relative to the above mentioned phase voltage by 90°. Spatial shift of axes of single-phase windings by 90° and time shift of the stress change curves by 90° on the outputs of windings allow obtaining a circular magnetic field in a air gap of the engine. At that it is important to say that the circular shape of a magnetic field in a gap between a stator and rotor remains in the slip range from 1 to 0. Performance characteristics calculated based on a mathematical model of such two-phase asynchronous motor are similar to characteristics of three-phase asynchronous motors [23].

The second significant drawback, common for slow-moving three-phase asynchronous electric motors, in particular low power coefficient, is not eliminated even in two-phase asynchronous engines of the described above design. The reason for such a drawback is that force lines of a magnetic field created by currents of a stator phases winding through each pair of poles cross twice an air gap that has a large magnetic resistance. To overcome the magnetic resistance of the air gap between the stator and rotor a significant magnetizing current is required. That comes from the expression [24]

$$I_\mu = \frac{P_0 F_0}{0.9 mw k_0},$$  \hspace{1cm} (3)

where $I_\mu$ is for the magnetizing current; $F_0$ is for the magnetic moving force per pair of poles; $m$ is for the number of motor phases; $w$ is for the number of turns in the phase winding; $k_0$ is for a winding coefficient. The negative effect of the magnetizing current on the power coefficient is particularly large in electromechanical low-power energy converters. Those converters are required for driving of the RPS plunger that lift liquid from wells with low production rate. For example, low-speed ($n_0 = 375 \text{ min}^{-1}$) asynchronous motors of 4.5 kW of power, designed to drive the plunger of RPS and produced by OOO “Vladimirskiy elektromotorny zavod” have the power coefficient of 0.46 [25].

Unsatisfactory values of the power coefficient and as a result low energy efficiency of low-speed asynchronous engines negatively affect the growth of the load of current-carrying elements of power supply systems and are constraining factors for their mass serial production.

Internal compensation of magnetizing currents of the stator windings is a new direction that contribute to improvement of the energy efficiency of slow-moving two-phase asynchronous motors. For that, two single-phase compensation windings in addition to two single-phase network windings are placed in grooves of the stator steel core. Outputs of compensation windings are connected to capacitors. To carry out the operation of such a motor, the network windings are connected to a three-phase alternating voltage network. A circular magnetic field, which in this case is created by the currents of these windings, induces electromotive forces in the compensating windings. Under the action of those electromotive forces en electric current is flowing along the compensating windings that has an advanced current. As a consequence, total magnetomotive force and electromotive force of the network windings increase. That causes a decrease in magnetizing currents of the network windings. Such a process continues until the electromotive
forces of the network windings together with the voltage drops at their resistances reach the values of the voltages that act on winding terminals.

Mathematical model of a two-phase compensated asynchronous motor of electrical drive of the plunger of RPS

In order to test work reliability of a two-phase compensated asynchronous motor a mathematical model is used [26, 27]. The equation of the magnetic field [28, 29] and Kirchhoff’s equations [30, 31] are used as a basis for a mathematical model performance. The number of equations equals to the number of one-phase windings placed in the grooves of a stator.

The equation of the magnetic field of an asynchronous motor with a rotor winding of the “squirrel cage” type is as follows

\[
\frac{1}{R_0^2} \frac{\partial^2 A}{\partial \varphi^2} - \mu_0 \gamma (1 + k_{a2}) \frac{\partial A}{\partial \varphi} - \mu_0 \gamma (1 + k_{a2}) \frac{\partial A}{\partial t} = -\mu_0 j_s, \tag{4}
\]

where \( A \) is for vector potential of a magnetic field (\( z \) is for constituent); \( R_0 \) is for mean radius of an air gap; \( \varphi \) is for tangential coordinate of the cylindrical coordinate system; \( \mu_0 \) is for magnetic constant; \( \gamma \) is for calculated conductivity of the conductors of the “squirrel cage” of the rotor, distributed in the motor gap; \( k_{a2} \) is for a coefficient of rotor scattering grooves; \( \omega \) is for angular rotational speed of a rotor; \( q \) is for coefficient that considers magnetic resistance of the motor magnetic circuit segments.

A boundary value problem described by equation (4) is solved taking into account boundary conditions of periodic type, expressing the equality of vector potentials and their derivatives at a conjugate point.

In case of sinusoidal nature of change of calculated quantities in time a solution of the problem can be simplified by shift to complex functions. In this case the differential equation (4) reduces to

\[
\frac{1}{R_0^2} \frac{\partial^2 \hat{A}}{\partial \varphi^2} - \mu_0 \gamma (1 + k_{a2}) \frac{\partial \hat{A}}{\partial \varphi} - \left( j \mu_0 \gamma (1 + k_{a2}) + q \right) \hat{A} = -\mu_0 \hat{j}_s, \tag{5}
\]

where \( \hat{A} \) is for a vector potential complex; \( j \) is for the imaginary unit; \( \hat{j}_s \) is for the stator current load complex.

The system of Kirchhoff equations compiled for the network and compensating stator windings is written as follows:

\[
U_A = j \omega \Psi_A + I_A (Z_A + jX_{2sA}), \tag{6}
\]

\[
U_B = j \omega \Psi_B + I_B (Z_B + jX_{2sB}), \tag{7}
\]

\[
0 = j \omega \Psi_{AK} + I_{AK} (Z_{AK} + jX_{2sAK} - jX_{CA}), \tag{8}
\]

\[
0 = j \omega \Psi_{BK} + I_{BK} (Z_{BK} + jX_{2sBK} - jX_{CB}). \tag{9}
\]

Equations (6)-(9) are written using complex quantities. Notation assumed is as follows: \( U_A, U_B \) are for phase and linear voltage; \( \Psi \) is for linkage; \( I \) is for current; \( Z \) is for full resistance; \( X_{2s} \) is for reduced induction resistance of a rotor; \( X_C \) is for capacitive resistance. Indexes \( A, B, AK, BK \) mean the belonging of this parameter to the corresponding network or compensation winding.

The linkages of the network and compensating windings of a two-phase asynchronous motor are caused by currents passing through the windings and are calculated by expressions

\[
\Psi_A = L_{1A} I_A + L_{12} I_B + L_{13} I_{AK} + L_{14} I_{BK}, \tag{10}
\]

\[
\Psi_B = L_{2A} I_A + L_{22} I_B + L_{23} I_{AK} + L_{24} I_{BK}, \tag{11}
\]

\[
\Psi_{AK} = L_{3A} I_A + L_{32} I_B + L_{33} I_{AK} + L_{34} I_{BK}, \tag{12}
\]

\[
\Psi_{BK} = L_{4A} I_A + L_{42} I_B + L_{43} I_{AK} + L_{44} I_{BK}. \tag{13}
\]

The right-hand sides of equations (10)-(13) contain complex self-induction coefficients \( L \) with two identical indexes and mutual inductance \( L \) with two different indexes.

After substituting of (10)-(13) into Kirchhoff’s equations (6)-(9) and performing the corresponding transformations a system of four equations where four currents are unknown such as two currents of the network windings and two currents of compensating windings:

\[
U_A = j \omega_0 L_{1A} I_A + Z_A I_A + jX_{2sA} I_A + j \omega_0 L_{12} I_B + j \omega_0 L_{13} I_{AK} + j \omega_0 L_{14} I_{BK}, \tag{16}
\]

\[
U_B = j \omega_0 L_{2A} I_A + j \omega_0 L_{22} I_B + Z_B I_B + jX_{2sB} I_B + j \omega_0 L_{23} I_{AK} + j \omega_0 L_{24} I_{BK}, \tag{17}
\]

\[
0 = j \omega_0 L_{3A} I_A + j \omega_0 L_{32} I_B + Z_{AK} I_{AK} + jX_{2sAK} I_{AK} + j \omega_0 L_{33} I_{BK}, \tag{18}
\]

\[
0 = j \omega_0 L_{4A} I_A + j \omega_0 L_{42} I_B + Z_{BK} I_{BK} + jX_{2sBK} I_{BK} + j \omega_0 L_{43} I_{BK}. \tag{19}
\]
In order to solve the system of equations (14)-(17) and calculate the values of the currents in the network and compensating windings, it is necessary to know the coefficients of self-induction and mutual induction. It is expedient to calculate these coefficients using the superposition method in a sequence given below.

A value of one of the currents at zero values of the other three currents is assumed. The equation of the magnetic field (5) is solved. As a result, the effective shaft power $P_2$, electromagnetic moment $M_{e,m}$, power coefficient $\cos \varphi$, efficiency factor $\eta$ are calculated using known expressions:

\begin{align*}
P &= \text{Re}(\bar{U}_A \bar{I}_A + \bar{U}_B \bar{I}_B), \\
P_{e,p} &= P - R_{A,s} \bar{I}^2_A - R_{B,s} \bar{I}^2_B, \\
P_2 &= P(1 - s), \\
M_{e,p} &= \frac{P_{e,p}}{\omega}, \\
\cos \varphi &= \frac{P}{U_A I_A + U_B I_B}, \\
\eta &= \frac{P_2}{P},
\end{align*}

where $\text{Re}$ is for a symbol of a real part of a complex number; $\bar{T}_A$, $\bar{T}_B$ are for complexes of acting current values conjugated with sets of acting values of currents of network windings; $R_{A,s}$, $R_{B,s}$ are for active resistances of network windings; $s$ is for slip; $\omega$ is for circular frequency;

\begin{equation}
\omega = \omega_0 \frac{1 - s}{p},
\end{equation}

An asynchronous motor was used as a model of a low-speed two-phase asynchronous electromechanical energy converter. An asynchronous motor has the following parameters:
- number of pairs of poles $p$ – 10;
- bore diameter of stator $d_c$ – 383 mm;
- air gap between stator and rotor $\delta$ – 0.554 mm;
- stator length in axial direction $L_a$ – 200 mm;
- number of turns $w_A$ of the network winding of a “$A$-$X$” phase – 80;
- number of turns $w_B$ of the network winding of a “$B$-$Y$” phase – 139;
- number of turns $w_{AK}$ of the phase compensation winding of a “$A$-$X$” – 35;
- number of turns $w_{BK}$ of the phase compensation winding of a “$B$-$Y$” phase – 35;
- calculated electrical conductivity of the rotor cell material $\gamma$ – 190 $\cdot 10^6$ Sm; 
- coefficient $q$ – 1320;
- active resistance of the network winding of a “$A$-$X$” phase – 0.36 Ohm;
- inductive resistance of the network winding of a “$A$-$X$” phase – 0.756 Ohm;
- active resistance of the network winding of a “$B$-$Y$” phase – 1.08 Ohm;
- inductive resistance of the network winding of a “$B$-$Y$” phase – 2.268 Ohm;
- active resistance of the compensation winding of a “$A$-$X$” phase – 0.02225 Ohm;

\begin{equation}
0 = j\omega_0 L_{a1} \bar{I}_A + j\omega_0 L_{a2} \bar{I}_B + j\omega_0 L_{a3} \bar{I}_K + (j\omega_0 L_{a4} + Z_{BK} + jX_{2WA} - jX_{CB}) \bar{I}_{BK}.
\end{equation}
– inductive resistance of the compensation winding of a “A-X” phase – 0.04725 Ohm;
– active resistance of the compensation winding of a “B-Y” phase – 0.02225 Ohm;
– inductive resistance of the compensation winding of a “B-Y” phase – 0.04725 Ohm;
– inductive resistance of the rotor winding, reduced to the parameters of the winding of a “A-X” phase – 1.37 Ohm;
– inductive resistance of the rotor winding, reduced to the parameters of the network winding of a “B-Y” phase – 4.11 Ohm;
– inductive resistance of the rotor winding, reduced to the parameters of the compensation winding of a “A-X” phase – 0.0856 Ohm;
– inductive resistance of the rotor winding, reduced to the parameters of the compensation winding of a “B-Y” phase – 0.0856 Ohm;
– capacitance in the compensating winding circuit of a “A-X” phase – 900 µF;
– capacitance in the compensating winding circuit of a “B-Y” phase – 900 µF;
– voltage complex on the phase network winding of a “A-X” – 219.4 V;
– voltage complex on the network winding of a “B-Y” phase – j380 V.

Modelling of the operating mode of an uncompensated two-phase asynchronous motor and two-phase asynchronous motor in which the magnetizing current and reactive power are compensated is done under the conditions where the slip value $s$ is 0.05. Some modelling results of the mentioned two-phase asynchronous motors are given below as a matrix of coefficients of self and mutual induction and the values of a number of their most important performance indicators (Table). Modelling results are shown in the vector diagrams as well (Fig. 1, 2). The diagrams include stress vectors on the stator network windings and vectors of their magnetomotive forces.

Matrix of coefficients of self and mutual induction of inductance $L$

\[
\begin{align*}
0.0148 - 0.0163j; 0.0256 + 0.0253j; 0.0064 - 0.0071j; 0.0064 + 0.0063j; \\
-0.0256 - 0.0253j; 0.0443 - 0.4890j; -0.0111 - 0.0111j; 0.0111 - 0.0122j; \\
0.0064 - 0.0063j; 0.0111 + 0.0110j; 0.0028 - 0.0031j; 0.0028 + 0.0027j; \\
-0.0064 - 0.0063j; 0.0111 - 0.0122j; -0.0028 - 0.0027j; 0.0028 - 0.00310j.
\end{align*}
\]

<table>
<thead>
<tr>
<th>Name of the parameter</th>
<th>No compensation</th>
<th>Compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current in the network winding of a “A-X” phase, A</td>
<td>14.63</td>
<td>11.95</td>
</tr>
<tr>
<td>Current in the network winding of a “B-Y” phase, A</td>
<td>8.45</td>
<td>6.90</td>
</tr>
<tr>
<td>Current in the compensation winding of a “A-X” phase, A</td>
<td>0</td>
<td>27.86</td>
</tr>
<tr>
<td>Current in the compensation winding of a “B-Y” phase, A</td>
<td>0</td>
<td>27.86</td>
</tr>
<tr>
<td>Electromagnetic power, W</td>
<td>4120.1</td>
<td>5137.7</td>
</tr>
<tr>
<td>Electromagnetic moment, N·m</td>
<td>131.15</td>
<td>163.54</td>
</tr>
<tr>
<td>Efficiency factor, rel. units</td>
<td>0.61</td>
<td>0.93</td>
</tr>
<tr>
<td>Power coefficient, rel. units</td>
<td>0.64</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Fig. 1. Vector diagram of stresses and magnetomotive forces of a single-phase asynchronous motor with no compensation.

Fig. 2. Vector diagram of stresses and magnetomotive forces of a single-phase compensated asynchronous motor.
Analysis of modelling results clearly shows that the values of the coefficients of self and mutual induction are invariant with respect to the current of the compensation windings. The higher the compensation the lower the currents in the network windings. There is an increase in the electromagnetic power and the electromagnetic moment. Energy parameters and energy efficiency of the motor increase significantly. Increase in energy parameters and decrease in currents, consumed from the electrical mains of the three-phase alternating voltage, contribute to reduction the current load of current carrying elements of the power supply systems. That creates a reserve for connecting of additional electric loads to existing electric networks. The above mentioned is illustrated by the vector diagrams shown in Fig. 1, 2.

It is clearly seen that there is a significant angle in a two-phase asynchronous motor with a network of winds on the stator between the voltage vectors on the network of windings and the vectors of the magnetomotive forces. There is a significant magnetizing component in the currents of the network windings that causes the consumption of reactive power from the supply network. Stacking of compensation windings in stator grooves and their connection to capacitors allow to eliminate a magnetizing component in the currents of the network windings. Angles of the phase shift between voltage terminals at the terminals of network windings and vectors of magnetomotive forces are in this case close to zero. A motor consumes only the active power from the AC electrical mains supply.

Conclusion

Studies of performance of a two-phase asynchronous compensated motor on a mathematical model allow asserting that the results obtained and conclusions remain valid for the slip range from 1 to 0. Production and wide implementation of two-phase asynchronous compensated motors in the plunger drive of RPS allow switching the operation regime of low productive oil wells to the most rational, increase the energy efficiency of the oil production and save energy resources.

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