The PMSM-drive submersible centrifugal pumps efficiency determining

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Abstract. In the paper, the problems of modelling and calculating the electromagnetic moment are considered. The study subjects are submersible induction and synchronous electric motors for centrifugal pumps. This task is relevant, because the requirements for oil production technology are growing. A brief description of the electric submersible pumps (ESPs) is given and the main design features of submersible motors are presented. The software for constructing and calculating the mathematical model of a submersible motor is selected. The field lines pictures in the section of motors are created. Characteristics of moment-current, moment-slip, moment-angle are built. Comparison results of two types of submersible motors are presented.

1. Introduction
The continuous development of industry is the reason for a steady increase in energy consumption [1,2]. Hydrocarbons remain the most popular type of fuel [3]. The issues of hydrocarbon production, transportation and storage are topical. When providing oil production sites, much attention is paid to energy efficiency [4]. There is a classification according to the level of efficiency: IE1 (Standard Efficiency), IE2 (High Efficiency), IE3 (Premium Efficiency), IE4 (Super Premium Efficiency) [5]. In this paper, it is proposed to consider the electric submersible pumps (ESPs). They are intended to extract reservoir fluid from oil producing wells. ESPs account for about a third of the operating wells. They produce about 60% of oil [6]. Submersible electric motor (SEM) is the drive for ESP. The electric motor determines the main power characteristics of the ESP. In this regard, the issues of mathematical modeling, energy and structural efficiency are interest.

In this work, the efficiency criterion is the electromagnetic torque created by motors with the same stator construction and the same current density in the stator windings.

2. Submersible electric motors (SEMs)
The main structural elements of the SEM are the rotor, stator, winding, shaft and motor housing (figure 1). Principal differences from general-purpose motors are in the design of the rotor [7]. It consists of individual packages (8 to 23), separated by a plain bearing. This is due to the requirements for the diameter of the shell [8].
Figure 1. The submersible electric motor components: 1 - Shaft; 2 - Flange connection; 3 - Mechanical seal; 4 - Motor housing; 5 - Flat Cable; 6 - Rotor; 7 - Stator; 8 - Winding; 9 - Thrust bearing; 10 - Rubber diaphragm [9]

The internal cavity of the SEM is filled with synthetic oil with a breakdown voltage of at least 30 kV/cm. It serves to lubricate friction parts of the engine and to remove heat [10]. Currently, submersible motors are available in various temperature versions (ambient temperature up to 200 °C) and with different dimensions of the housing, oriented to typical well diameters.

Magneto-electric machines are used in many industries. This is due to the appearance of permanent magnets with a large coercive force and residual induction. For example, they are permanent magnets based on neodymium alloys [11]. PMSM have good energy characteristics, a simple construction and wide possibilities of speed control.

3. Pumping stations control systems

The submersible pump unit functional scheme (figure 2) includes a rectifier unit, a voltage controller, an inverter, a transformer, a control system, voltage and current sensors, a submersible telemetry unit, a submersible electric machine and a centrifugal pump [12].

Figure 2. The submersible pump unit functional scheme

The rotor speed determines the capacity of the pump. It is regulated by changing the voltage at the input of the inverter according to the information from the sensors. The submersible telemetry unit monitors and sends information to the control system about the current status of the pumping unit. In the event of a malfunction, the system automatically switches off the ESP or generates an error signal, the code of which corresponds to the detected malfunction.

The control object is deep underground. Therefore installation of additional measuring devices and converters directly on it is inexpedient. This solution is associated with additional errors and reduces the reliability of the ESP [13].

The need to use the rotary encoder is a significant disadvantage of PMSM-drive. This defect may be eliminated through the use of sensorless control methods [14].
4. Method and software for modelling

Recently, the finite element method has been widely used to calculate fields [15-17]. There are many types of software using this method. The application of this method to solve various problems is presented in [18-22]. In this paper, Elcut software is used to analyse electrical machines. Features Elcut allow you to solve multiphysical problems.

5. Initial data for modelling

One sample is selected for creating and determining the SEM geometrical model. The prototype is PEDN70-130-1950. The main parameters of this electric motor are given in table 1.

| Type                | Rated power | Rated voltage | Rated current | Efficiency | Power factor | Slip |
|---------------------|-------------|---------------|---------------|------------|--------------|------|
| PEDN70-130-1950     | 70          | 1950          | 27.5          | 84.4       | 0.893        | 4.6  |

The geometric model of the electric motor is represented by the cross section of the stator and the rotor package (figure 3,4). The stator has 24 slots. The rotor has 37 slots. The stator and rotor slots are closed [23]. The winding of the stator and rotor is copper. The air gap is 1.5 mm. The stator and rotors are made of electrical steel ST 2013.

![Figure 3. The induction SEM model](image)

![Figure 4. The synchronous SEM model](image)

The shaft is made hollow to improve cooling. The three-phase stator winding is located in the slots in such a way as to create 2 pairs of poles. The current density in the stator windings for this type of motor is 7 A/mm² [6].

| Type                | Current density | Stator winding permeability | Rotor winding permeability | Rotor and stator steel permeability | Rotor winding conductivity | Magnets coercive force |
|---------------------|-----------------|-----------------------------|---------------------------|-----------------------------------|---------------------------|------------------------|
| Induction SEM       | 7000000         | 1                           | 1                         | B=f(H)                            | 4000000                   | -                      |
| Synchronous SEM     | 7000000         | 1                           | 1.03                      | B=f(H)                            | -                         | 1000                   |

To simulate a synchronous SEM with permanent magnets, it is necessary to change the induction SEM construction [24]. The short-circuited rotor winding is replaced by four permanent magnets based on
the Nd-Fe-B alloy. The current density, location of the stator windings, material and dimensions of the stator and rotor are the same. The initial data for modelling are shown in table 2.

6. Simulation results analysis

The simulation results are shown in figure 5 and figure 6. The results of induction and synchronous SEM simulation show the poles of the rotor and stator. The symmetry of the magnetic flux lines allows us to conclude that the models are correctly constructed. The electromagnetic field map analysis shows that the magnetic system of a synchronous SEM using more efficient.

![Figure 5. The induction SEM simulation result](image1)

![Figure 6. The synchronous SEM simulation result](image2)

The Elcut program allows to perform a series of sequential calculations. This property can be used to build the torque characteristics of the studied machines. To build the torque-slip characteristic of the induction SEM, it is necessary to change the stator current frequency from 50 to 1 Hz (slip imitation). To build the torque-angle characteristic of the synchronous SEM, it is necessary change the rotor position relative to the stator from 0 to 180 degrees [25]. The built characteristics are shown in figure 7 and figure 8. The synchronous SEM characteristic distortion due to the higher harmonics influence.

![Figure 7. The induction SEM torque-slip characteristic](image3)

![Figure 8. The synchronous SEM torque-angle characteristic](image4)

The built-in Elcut means can measure the torque. It is necessary to include the rotor in the integration circuit and use the integral calculator. As a result of the simulation, the induction SEM torque $T_I = 480$ N·m. The synchronous SEM torque $T_S = 629$ N·m.
It is necessary to construct the torque-current characteristic. To do this, the simulation is repeated for stator current density from 0.5 to 1.5 times the nominal value. The calculation results are summarized in table 3 and shown in figure 9.

**Table 3. Motor torque measurement results**

| Current density $J$ | $T_r$, N·m | $T_s$, N·m |
|--------------------|------------|------------|
| 0.5 $J$            | 120        | 333        |
| 0.6 $J$            | 173        | 391        |
| 0.7 $J$            | 235        | 449        |
| 0.8 $J$            | 307        | 508        |
| 0.9 $J$            | 389        | 567        |
| $J$                | 480        | 629        |
| 1.1 $J$            | 571        | 692        |
| 1.2 $J$            | 720        | 756        |
| 1.3 $J$            | 817        | 821        |
| 1.4 $J$            | 895        | 888        |
| 1.5 $J$            |            | 957        |

![Figure 9. Motor torque measurements results.](image)

The constructed graph (figure 9) demonstrates nonlinear torque character asynchronous SEM. A synchronous SEM demonstrates a practically linear character.

7. Conclusion

In the course of work, geometrical models were created for induction and synchronous SEM. The modeling was performed using the finite element method. Characteristics of moment-current, moment-slip, moment-angle built. The distortion by the higher harmonics of the synchronous SEM moment is determined. Analysis of the simulation results showed that in a synchronous SEM the magnetic system is used more efficiently. Replacing the short-circuited rotor on a rotor with permanent magnets allowed a 23% increase in the torque without changing the current density in the stator windings. The the torque-current characteristic in the range 0.5-1.5 has revealed a nonlinear dependence in the case of induction SEM. Synchronous SEM have a linear dependence in the same conditions. Analysis of the results allows to make certain conclusions. First, when using SMPM as a SEM, it is possible to increase the torque without changing the dimensions and current loads of the machine. Secondly, it is possible to obtain a torque comparable with an asynchronous machine at a lower power consumption, and hence with less electrical losses. Based on this, the use of the PMSM for submersible electrical centrifugal pumps motor is efficient.
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