Verification for the simulation model of submersible electric motor with downhole compensator based on the bench tests results

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Abstract. The bench tests results of submersible electric motor with downhole reactive power compensator are presented in this study. The decrease in the current consumption by 13\% and the increase in the power factor from 0.84 to 0.95 are recorded according to the test results. A simulation model of a submersible electric motor with a downhole reactive power compensator is developed. The data obtained on the simulation model are compared with the bench tests results. It is found that the discrepancy between the calculated and experimental data is less than 10\%. Consequently, the simulation model adequately reflects the electromechanical processes of the real object.

1. Introduction
It is known that one of the effective ways to reduce power losses in air and cable power lines at active-inductive load is the compensation of the inductive component of reactive power \cite{1, 2, 3, 4}. The individual, the group \cite{4} and the centralized \cite{5} compensations are distinguished versus the method of connection compensating device (CD). In the oil industry, the power supply systems of oil-producing well clusters mainly use the group reactive power compensation (figure 1(a)). The compensating device is installed on the baras of the complete- transformer substation 10/0.4 kV. It can reduce the current inductive component and power loss in the power supply line with this type of compensation. CD power is selected based on the maintenance of the required reactive power factor at the connection point not lower than $\text{tg} \varphi=0.1$.

However, the use of group reactive power compensation does not reduce the inductive component of the current in the outgoing cables supplying the submersible electric motors (SEM). As the length of the cables increases, the loss of active power increases. It leads to additional financial costs for oil production. In some fields, the length of cables feeding SEM can reach 3500 m \cite{6, 7, 8}.

According to the \cite{9, 10, 11} study it is proposed to use downhole reactive power compensators (DRPC) for improving the energy efficiency of the electrical installation complex for oil production. That is, to implement the concept of individual reactive power compensation. In this type of compensation, the downhole compensator is installed directly into the oil well and connected in parallel to the submersible electric motor (figure 1(b)). The quantity and power of DRPC is based on the quantity and power of SEM. The mathematical and simulation models proposed by the authors make it possible to assess the introduction feasibility of the downhole reactive power compensators in the oil fields.
The purpose of the article is to report on the practical implementation of downhole compensation devices and verification of the simulation model of a submersible electric motor with a downhole reactive power compensator based on the bench tests results.

2. Materials and Methods
To confirm the adequacy of the developed simulation [12] and mathematical models [9, 10, 11], a prototype of a downhole reactive power compensator (figure 2) with power of 30 kvar was developed. DRPC consists of a durable sealed container, inside which there is a high-temperature cosine capacitor. Connection to the submersible motor is carried out by means of a coupling with sealing glands.

Figure 1. Schematic diagram of power supply ESP: a) group compensation; b) individually compensation.

Figure 2. The DRPC prototype
The submersible electric motor ED-Y 63-117 M5B 5 was chosen for testing. SEM passport details are given in table 1. Bench tests were carried out in the licensed laboratory of the submersible equipment for oil production LLC «Almaz» producer factory, town Radugeniy.

**Table 1.** Technical characteristics of submersible motor

| Characteristic                      | Value  |
|-------------------------------------|--------|
| Rated voltage \( U_{m.nom} \), V    | 1040   |
| Rated active power \( P_{m.nom} \), kW | 63     |
| Rated rotation speed \( n_{m.nom} \), rpm | 2910   |
| Rated coefficient of efficiency \( \eta_{m.nom} \), % | 84.5   |
| Rated power factor \( \cos \phi_{m.nom} \) | 0.84   |
| Rated current \( I_{m.nom} \), A     | 51     |
| Nominal moment \( M_{m.nom} \), N-m  | 212    |
| Frequency of starting current       | 5.1    |
| Frequency of starting moment        | 1.5    |
| Frequency of maximum moment         | 2.3    |
| Moment of inertia \( J \), kg-m²     | 0.46   |
| Nominal slip \( s_{m.nom} \), %      | 3.0    |
| Critical slip \( s_c \), %           | 23.8   |

Consequently of the research the parameters of the considered equivalent circuit of the motor, expressed in absolute and relative units are found [12].

**Table 2.** Parameters of the motor equivalent circuit in absolute and relative units

| Parameters                          | Physical units, Ohm | Relative units, p.u. |
|-------------------------------------|---------------------|----------------------|
| Active resistance of stator winding | \( R_{1m} = 1.35 \) | \( R^{*} = \frac{R_{1m}}{Z_b} = \frac{1.35}{12.8} = 0.105 \) |
| Inductive resistance of stator winding | \( X_{1m} = 0.995 \) | \( X^{*} = \frac{X_{1m}}{Z_b} = \frac{0.995}{12.8} = 0.077 \) |
| Reduced active resistance of the rotor winding | \( R'_{2m} = 0.676 \) | \( R^{*} = \frac{R'_{2m}}{Z_b} = \frac{0.676}{12.8} = 0.053 \) |
| Reduced inductive resistance of the rotor winding | \( X'_{2m} = 0.995 \) | \( X^{*} = \frac{X'_{2m}}{Z_b} = \frac{0.995}{12.8} = 0.077 \) |
| Inductive resistance of magnets circuit | \( X_{mm} = 21.05 \) | \( X^{*} = \frac{X_{mm}}{Z_b} = \frac{21.05}{12.8} = 1.64 \) |

The simulation model of a submersible electric motor with a downhole reactive power compensator creation imposes the fabricated blocks of electrical devices included in the Matlab/Simulink SimPowerSystem: three-phase programmable voltage source; asynchronous machine squirrel cage and three-Phase Series RLC Load. The three-phase U-1 block is used for measuring the instantaneous current values and voltage parts circuit [13]. The initial conditions and the calculated parameters of submersible electric motor is given in [12]. The developed simulation model of a submersible electric motor with a downhole reactive power compensator is shown in figure 3.
3. Results

The performance characteristics of the submersible electric motor ED-Y 63-117 M5B 5 obtained during the bench tests are shown in figure 4.

![Figure 3. A simulation model of a submersible electric motor with a downhole compensator](image)

Comparison of experimental performance characteristics (data 1) with the characteristics obtained on the simulation model (data 2) is given in table 2. The study is conducted in a fixed operating mode of SEM with the static moment (Mc) application at the level of 40%, 60%, 80%, 100%, 120% from nominal moment.

![Figure 4. Performance characteristics of submersible electric motor with downhole reactive power compensator](image)
### Table 3. Comparison of experimental and obtained characteristics

| Мс, % | Speed, rpm | Current, A | Consumed active capacity, kW | Coefficient of capacity cos φ |
|-------|------------|------------|------------------------------|-------------------------------|
|       | 1          | 2          | Δ, %                         | 1 | 2 | Δ, % | 1 | 2 | Δ, % |
| 40    | 2950       | 2944       | 0.2                          | 20.8 | 20.2 | 3.0 | 33.6 | 31.3 | 7.3 | 0.89 | 0.86 | 3.5 |
| 60    | 2924       | 2914       | 0.3                          | 27.7 | 27.1 | 2.2 | 45.5 | 44.9 | 1.3 | 0.922 | 0.918 | 0.4 |
| 80    | 2890       | 2876       | 0.5                          | 36.4 | 35.9 | 1.4 | 61.7 | 61.3 | 0.7 | 0.938 | 0.945 | -0.7 |
| 100   | 2858       | 2838       | 0.7                          | 45.0 | 44.6 | 0.9 | 76.8 | 76.9 | -0.1 | 0.945 | 0.954 | -0.9 |
| 120   | 2831       | 2801       | 1.1                          | 53.6 | 52.9 | 1.3 | 91.7 | 91.5 | 0.2 | 0.948 | 0.957 | -0.9 |

4. Discussion

During the performance analysis (figure 4), an increase in the electrical power factor of the «SEM-DRPC» node from 0.84 to 0.945 was recorded with the application of the nominal moment of 212 Н·м. The decrease in the current consumption relative to the nominal current of the submersible motor is 13%. The efficiency remained unchanged at 0.84 level. This is due to the fact that the downhole reactive power compensator does not affect the electromechanical processes in the submersible motor.

The verification of the simulation model of the submersible electric motor ED-Y 63-117 M5B5 with the downhole reactive power compensator shows that the model adequately reproduces the electromechanical processes of real devices. The calculated values deviation of the consumed current from the experimental data is 0.9 % in the nominal mode and for the active power consumption it is 7.3 %. The maximum error for the current is 3.0 % and it decreases with increasing load to 0.9 %, taking into account the permissible measurement errors on the test benches (not more than 0.5 %), corresponding to the area of low loads.

Thus, the obtained deviations are less than the permissible ones accepted in engineering practice. Therefore the developed simulation model adequately reflects the electromechanical processes of the «SEM-DRPC» node.

5. Conclusions

A simulation model of a submersible electric motor with a downhole reactive power compensator is developed. The discrepancy between the experimental data and the data obtained on the simulation model is less than 10 %. Therefore, the simulation model adequately reflects the electromechanical processes of the «SEM-DRPC» node.

The increase in the power factor from 0.84 to 0.945 at rated load and the decrease in current by 13% were recorded during bench tests of the submersible electric motor ED-Y 63-117 M5B5 with the downhole reactive power compensator. It is advisable to conduct further studies of downhole reactive power compensation devices in a real well with an assessment of the economic efficiency of their implementation and evaluation of operating modes.

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