Investigation of transients in a submersible electric motor with a downhole compensator

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Abstract. Currently, the energy efficiency improving into the oil production is an important task. The main electricity consumer in the electrical complex structure of the electric centrifugal pumps’ installation is a submersible asynchronous electric motor. The power factor of these electric motors varies from 0.75 to 0.85. It leads to the losses’ increasing in the conductive elements of the complex. The use of downhole reactive power compensators is the most potential way to increase the power factor into the submersible asynchronous electric motors. In the course of pilot tests there are some cases of the protection devices for downhole compensators’ false triggering. It is recorded when the control station is switched off. It leads to the energy efficiency decreasing into the oil production. The purpose of this study is to research the transients in a submerged asynchronous electric motor equipped by the downhole compensator when the power supply is switched off. The task of the study is to determine the transient process’ parameters, in order to prevent false triggering of the downhole compensator protection devices. Simulation modeling of a submerged electric motor with a downhole compensator is performed in the Matlab Simulink. A simulation model of a submerged electric motor with a downhole compensator is developed to study transients when the power supply is switched off. The characteristics for the transient process of the voltage and current into the downhole compensator are obtained during the simulation modeling. The current surge for the capacitors’ discharge of the downhole compensator is 260.7% relative to the rated current at the time of the power supply disconnection. Prevention measures off false triggering for automatic shutdown devices of the downhole compensator are proposed.

1. Introduction

Improving the energy efficiency of oil production is an important task. This task contributes to reducing the oil production cost and increasing its competitiveness in the world market. The total electricity consumption of the oil industry was about 55 billion kWh per year in 2020. It is 5 % of the total electricity generation in our country [1]. There are some currently used methods in oil production. The main share of electricity consumption is made by the mechanized production method of the electric centrifugal pump installations (ECP). The main share of electricity is produced by the floating oil’s lifting. It is from 55 % to 62 % of the total electricity consumption.

The main electricity consumer in the structure of the electrical complex of the ECP is a submersible electric motor. It rotates the shaft of the electric center pump. Currently, two main types of submersible electric motors are used. They are asynchronous and valve submersible electric motors. The most widespread are asynchronous electric motors with a short-circuited rotor [2-5]. They have a
lower cost and a high failure time of about 790 days according to GOST 30195-94 with the same power characteristics. The submersible asynchronous electric motor consists of a stator, a rotor, a head, a base and a current lead unit. The stator is a sealed housing made of a special pipe. There is a magnetic core made of sheet electrical steel inside. A three-phase winding is laid in the slots of the stator. Its phase conductors are connected according to the "star" scheme. The rotor is a set of packages. The copper rods are inserted in their grooves and they are connected at the ends by copper rings. The efficiency and power factor of submersible asynchronous motors range from 79 % to 85 % [6, 7]. It depends on its design parameters and power. The potential capacity to increase the efficiency by reducing mechanical losses in the bearings and power losses in the stator winding conductors is exhausted. The use of electrical steel with a smaller sheet thickness for the production of the stator magnetic circuit increases the cost of submersible electric motors. It is not economically effectually.

The use of the downhole reactive power compensators (DRPC) [8, 9] is the way to increase the power factor of a submerged asynchronous electric motor and the energy efficiency of oil production in the ECP. The authors present the theoretical research’s results of improving the oil production energy efficiency in the study [10, 11]. It is shown that the DRPC can increase the energy efficiency of mining up to 12.5 % by increasing the power factor of the submersible asynchronous motor to 0.95.

The downhole compensator contains a strong sealed housing made of a special pipe to provide air space and a pressure of 1 atm, [8] by its construction. Inside the housing there are capacitors and an automatic shutdown device. The automatic shutdown device disconnects the capacitor from the mains in case of its premature failure. It can be due to a short circuit or the dielectric breakdown. It eliminates the failure of the submersible equipment into the ECP. The DRPC is connected along to the submersible electric motor inside the well. The downhole compensator performs the function of an energy storage device in the structure of the ECP electrical complex. The stored energy in the DRPC capacitors is transferred to the network when the control station is switched off. It can happen, for example, when the ECP is stopped or the protection is triggered.

The characteristic of the capacitor discharge current’s transient process is determined by the resistance of the network section from the control station to the submersible electric motor and the voltage level. The false triggering will produce if the discharge current of the DRPC capacitors is higher than the tripping current of the automatic shutdown device. The DRPC automatic shutdown device is switched off only without the possibility of subsequent activation. The measures are needed to reduce the impact of transients on the protection operation of the downhole compensator.

There is no information about studies of transients occurring in the ECP electrical complexes with downhole compensators in the scientific and technical literature. It is due to their recent appearance. The relevance of the transient’s study is successful by taking into account the positive economic effect of the DRPC introduction and the share of electricity consumption into the oil industry from the total generation of electric energy.

2. Materials and Methods
The DRPC is an energy storage device. The total resistance of the system is determined mainly by the submersible motor resistance and the downhole compensator resistance at the moment of the control station switching off. The false protection operation may occur to the submerged electric motor when the downhole compensator is discharged. The energy efficiency of oil production decreases consequently. The expensive descent-lifting operations are required during repair and restoration work to activate the protection since the automatic shutdown device of the DRPC works only for disconnection.

It is necessary to determine the parameters of the transition process in order to develop the necessary measures to prevent false triggering of the DRPC automatic shutdown devices.

The submerged three-phase asynchronous electric motor of the 2ED-63-117 brand with a power of 63 kW, equipped with a DRPC with a power of 35 kV is choosen as the research object.

Nowadays, the simulation modeling becomes widespread due to the capacity increasing in the electronic computers. It allows solving the problems of modernization, operation and technical objects’ construction with minimal financial costs. Modern software for the electrical systems’ study is represented by the following products. They are Electronics Workbench, LabVIEW, Matlab, NL5
Circuit Simulator, System View, Simulator and others. These software programs include libraries that contain ready-made blocks of electrical equipment and electronic elements. The Matlab Simulink is the most available and popular software products among the scientific and technical community. It reflects the processes occurring in electrical devices with a sufficient degree of accuracy [12].

The blocks of the libraries SimPowerSystem, Sinks and User-Defined Functions of the Matlab Simulink software complex are used during the construction of the simulation model. They are used to study the transients in a submersible electric motor with a downhole compensator.

The power supply is represented by the "three-phase programmable voltage source" unit in the model. The effective value of the line voltage of the power supply is 1040 V and the frequency is 50 Hz.

The power supply is switched off by the "ideal switch" unit. The key operation is controlled by the logic block. The "ideal switch" unit is controlled by the "step" unit (step signal generator). The ideal key is closed if the control signal 1 is applied to the logic block and it is turned off when the signal 0 is applied. In the "Breaker" block, switching on/off occurs when the current passes through the zero value. But in the "ideal switch" block, the key can be opened as in real networks, at any current value. In this regard, the processes modeled by the "ideal switch" block are close to the real transients that occur in mains during disconnection.

The submersible asynchronous electric motor in the model is represented by the "Asynchronous machines pu units" (asynchronous machine with a short-circuited rotor). The block operation is described by a T-shaped substitution scheme. The block includes the electrical part, represented by a fourth-order model of the state space and the mechanical part in the form of a second-order system. All electrical variables and machine parameters are given to the stator. The initial equations for the electrical part of the machine are written for the two-phase dq coordinate system.

The parameters for the model of the investigated submersible electric motor by the 2ED-63-117 brand are given in table 1 [13].

| Characteristic                                      | Value  |
|-----------------------------------------------------|--------|
| Rated voltage, V                                    | 1040   |
| Rated apparent power, kVA                           | 88757  |
| Active resistance of the stator winding, Ohm         | 1.0    |
| Inductance of the stator winding, mH                 | 3.17   |
| Reduced active resistance of the rotor winding, Ohm  | 0.676  |
| Reduced inductance of the rotor winding, mH          | 3.17   |
| Inductance of the magnetization circuit, mH          | 67.0   |
| Moment of rotor's inertia, kg·m²                     | 0.46   |
| Coefficient of friction, N·m·s                       | 0.022  |

The authors verify the accepted model of the submersible electric motor with the bench tests' results in [11] the study. It is established that the relative error of the obtained electromechanical characteristics on the model in the nominal mode does not exceed 5 %. Therefore, the model meets the requirement of adequacy for the displayed characteristics.

The downhole compensator is represented in the model by the "Three-Phase Series RLC Load" block (three-phase RLC load). The parameters of the bloc are set with DRPC rated power of 35 kV, a rated voltage of 1040 V and a frequency of 50 Hz.

The operation’s simulation of the electric centrifugal pump is carried out by the "Fcn" (function). The mechanical characteristic for the pump load moment on the shaft of the submersible electric motor is described by the equation:
\[ M_s = M_0 + (M_0 - M_{\text{nom}}) \cdot \left( \frac{\omega}{\omega_{\text{nom}}} \right) \sqrt{\frac{H_0 \cdot \left( \frac{\omega}{\omega_{\text{nom}}} \right)^2}{H_0 - H_s}}, \]  

where \( M_0 \) is the idling torque, N\cdot m; \( M_{\text{nom}} \) is the resistance moment at rated load, N\cdot m; \( \omega \) is the angular velocity of the centrifugal pump shaft, rad/s; \( \omega_{\text{nom}} \) is the nominal angular velocity of the centrifugal pump shaft, rad/s; \( H_0 \) is the pump head at zero flow, m; \( H_s \) is the static head, m.

The Scope block (oscilloscope) is used to observe the changes into the studied signals in the function of time into the simulation process. The Display block (digital display) is used to display the value of the studied signal in quantity.

3. Results

A simulation model of a submerged asynchronous electric motor with a downhole reactive power compensator for studying transients when the power supply is switched off is shown in figure 1.

![Simulation model of a SEM with a DRPC in Matlab Simulink](image)

**Figure 1.** Simulation model of a SEM with a DRPC in Matlab Simulink: \( f(u) \) – block for setting a function that simulates the operation of an electric centrifugal pump.

The characteristics for the transient process of the discharge current and the DRPC voltage are shown in figure 2 and figure 3 respectively. The time interval from 0.55 s to 1.0 s is shown. The keys are switched off at the 0.58 s time, when the voltage on the DRPC has the maximum value.

The electromagnetic torque dependence on the shaft is shown in figure 4. The speed dependence of the submersible motor on time is shown in figure 5. The engine starts at time 0 s. The engine switches to steady-state mode at 0.55 s.

The transient current characteristics of the rotor and stator for the submersible motor from time are shown in figure 6 and figure 7 respectively.
Figure 2. The DRPC discharge current phase_a dependence on time

Figure 3. The voltage dependence on time at the DRPC

Figure 4. The torque on the shaft dependence on time for the submersible motor
4. Discussion
The analysis of the DRPC current dependence (figure 2) shows that the current surge occurs due to the capacitors’ discharge at the moment of the power supply disconnection. Peak value of current switching is 16.1 A. Peak value of the current after switching is 71.7 A. Nominal peak value current is 27.5 A. The DRPC transient current is characterized by its oscillatory nature and decaying amplitude. The oscillatory nature is caused by the energy exchange between the DRPC capacitors and the inductance of the stator winding and the magnetization circuit of the submersible electric motor (figure 7). The periodic energy exchange continues until the accumulated energy is dissipated as heat on the active resistance of the mains section after switching.

The voltage on the capacitor cannot be changed instantly (abruptly) according to the switching laws of the theoretical foundations for electrical engineering. It is consistent with the characteristic of the transient process in figure 3. The amplitude value of the voltage is equal to 1470 V before and after
switching. The characteristic of the voltage transition process on the DRPC has an oscillatory character, decaying amplitude.

The electromagnetic torque of the submerged electric motor in steady-state mode is 202 N·m. The electromagnetic torque (figure 4) and the rotor current (figure 6) are reduced to zero at the moment of the transition process. The rotation speed of the rotor shaft gradually decreases when the power supply is switched off (figure 5) due to the available inertia.

It is necessary to provide some measures to reduce the current surge of the discharge capacitors in order to prevent false triggering into the automatic shutdown device of the downhole compensator. They are - programming the control station so that the shutdown is carried out when the voltage amplitude has a minimum value; install current-limiting diodes in the control circuit.

5. Conclusions
A simulation model of a submerged asynchronous electric motor with a downhole compensator is developed for studying transients in the Matlab Simulink. The characteristics of the transient current and voltage DRPC, rotor current and stator submersible motor are obtained. The surge into the discharge current of the DRPC capacitors is recorded at the power supply switching off time. It is in amount of 260.7 % relative to the rated current.

References
[1] Ivanovsky V N 2011 Engineering practice 6 pp 51–57
[2] Sagdatullin A M 2019 Iст Int. Conf. on Control Systems, Mathematical Modelling, Automation and Energy Efficiency (Lipets, Russian) DOI: 10.1109/SUMMA48161.2019.8947544
[3] Bafghi M H B and Vahedi A 2018 IOP Conf. Ser.: Mater. Sci. Eng. 433 012091
[4] Romanov V S and Goldstein V G 2018 J. Phys.: Conf. Ser. 944 012099
[5] Gizatullin F A et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 537 062006
[6] Shubin, S S et al 2021 Bulletin of the Tomsk Polytechnic University: Engineering of geo-resources 1 pp 204–214
[7] Kovalev V Z et al 2019 Int. Scientific and Technical Conf. Dynamics of Systems, Mechanisms and Machines (Omsk, Russia) DOI: 10.1109/Dynamics.2018.8601471
[8] Kopyrin V A et al 2016 Pat. of the Russian Federation No 159811 appl. 21.09.2015, publ. 20.02.2016
[9] Kopyrin V A et al 2018 Pat. of the Russian Federation No 189025 appl. 12.10.2018, publ. 05.07.2019
[10] Kopyrin V A 2018 Bulletin of the Tomsk Polytechnic University: Engineering of geo-resources 9 pp 117–124
[11] Kopyrin V A et al 2019 IOP Conf. Ser.: Journal of Physics: Conf. Series 1260 052012
[12] Chernykh I 2007 Modeling of electrotechnical devices in MATLAB. SimPowerSystems and Simulink (Moscow, DMK) 288 pp
[13] Kopyrin V A et al 2018 Int. Multi-Conf. on Industrial Engineering and Modern Technologies (Vladivostok, Russia) DOI: 10.1109/FarEastCon.2018.8602539

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