IOP Conf. Series: Earth and Environmental Science **87** (2017) 032027 doi:10.1088/1755-1315/87/3/032027

Increasing Mud Pump Motor Reliability against Malfunctions of DC Motor Excitation System

O.V. Nikulin[1], V.A. Shabanov[2]

[1]Chief Power Engineer of Management Company Tatburneft LLC Almetyevsk, 51 Fahretdin Street, 423450, Russia
[2]Prof. Head of Chair "Electrotechnical and Electrical Equipment of Enterprises", Ufa State Petroleum Technological University (USPTU), 1Kosmonavtov Street, 450044, Russia

E-mail: oleg309@yandex.ru.ru

Abstract. The most widely used drilling machinery, such as mud pumps, draw-works, and rotors, use direct-current (DC) motors with independent excitation as the electric drive. Drilling machinery drives operate in harsh ambient conditions, including those with the presence of moisture, dust and vibration, which increases the malfunction rate of both drilling equipment and their electric drives. One of the frequently encountered malfunctions are DC motor excitation coil faults, which disrupt the normal functioning of electric drives, often leading to shutdown of the drilling process. In a four-pole DC motor, the malfunction of one coil leads to lack of excitation current in just one coil pair, while the other pair remains functional. In this case, DC motors and drilling equipment can remain operational, which would allow for continuing the drilling process. This paper considers the possibility of operation of a DC motor on a drilling rig in those cases when one pair of excitation coils is non-functional, and describes the device for switching between the excitation coils and the auxiliary winding in a DC motor with independent excitation.

1. Introduction
The modern gas and petroleum drilling rig is a complex of mechanical and other equipment, used for oil well construction operations. Today, the mandatory requirement for basic machinery is to include a variable speed electric motor. Recently, this requirement also became applicable to auxiliary equipment. Even though new drilling rigs use frequency-controlled electric drives as a replacement for DC electric drives, the latter nonetheless remain widely used, and will be used for a long time to come [1-6]. Considering the harsh operating conditions of electric drives in drilling rigs, the task to increase electric drive reliability used in drilling rigs seems relevant [7]. This article reviews the means to preserve the functionality of the electric drive, used in drilling rig during malfunctions in the DC motor's drive excitation system.

2. Methods used for examination of the magnetic circuitry of a direct-current drive
The research was conducted on a virtual electric complex model of a mud pump, created in the Simulink environment (Figure 2). The electric complex model includes a subsystem (model) of the magnetic circuit, model of the DC motor, model of the mud pump (controller and load-generating unit), as well as an auxiliary calculation subsystem.

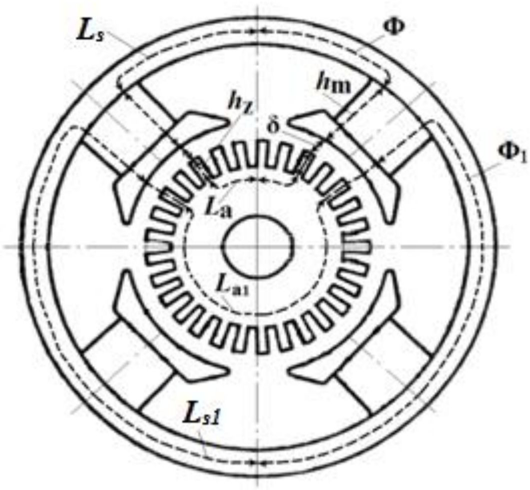

Figure 1. Magnetic circuit of the DC machine, in case of malfunction of one of the excitation coils: δ – air gap, h_z – armature teeth, L_a, L_{a1} – armature core, h_m – poles, L_s, L_{s1} – stator core.

The main component of the model is the model of the magnetic circuit of the machine during malfunctions in the excitation system. The magnetic circuit of the DC machine during malfunction of one of the excitation windings is shown in Figure 1. In order to analyze the magnetic circuit, two magnetic fluxes Φ and $Φ_1$, should be considered, which have different lengths, values of magnetic flux and magnetomotive forces. The magnetic circuit model is used for calculation of the magnetizing forces on subcircuits Φ and $Φ_1$. In order to account for the magnetization of the steel on the magnetic subcircuits, the authors used the one-dimensional Look-UpTable, which specifies in a tabular form the magnetization curve *B(H)* of electric steel. An auxiliary calculations subsystem is used for the calculation of: magnetic fluxes Φ and $Φ_1$, and the developed electromagnetic torque. For the modeling of the DC motor, the authors used transfer functions for the armature current and rotation speed at zero starting conditions [8].

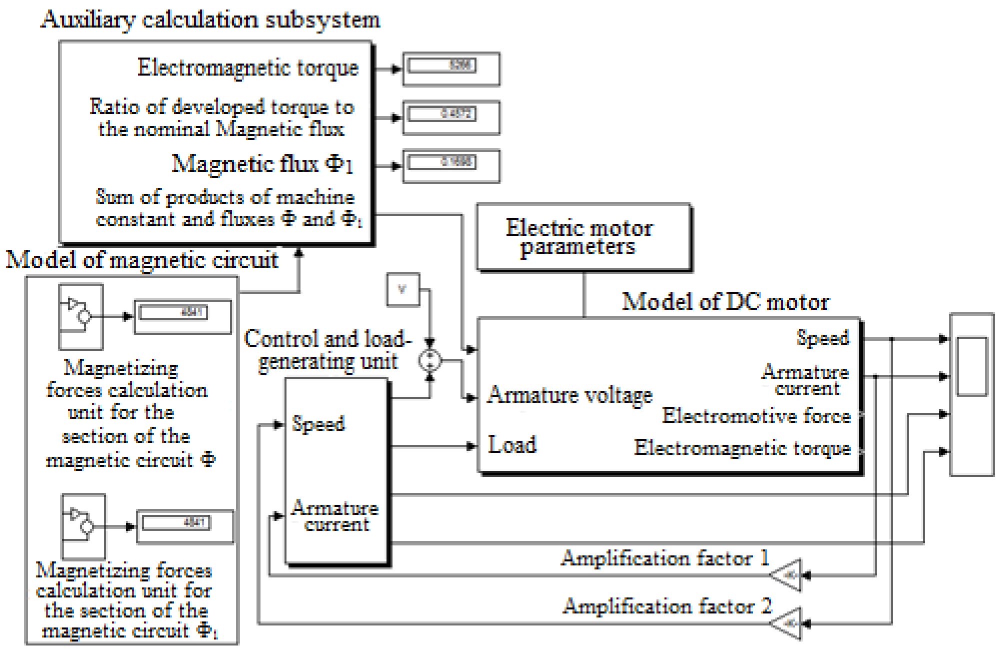

Figure 2. Virtual electric drive model of mud pump

3. Modeling and field testing results

Modeling results were tested on an operational drilling rig. During drilling of well No. 20782, the depth of 1665 m, owner Tatburneft LLC, the authors registered a malfunction of one excitation coil pair at a depth of 760 m. In order to continue operation, the authors switched the electric motor to operate with one pair of poles of the excitation winding. Figure 3 shows the discharge pressure curve of the mud pump at 760-815 m drilling interval, exported from the drilling parameters control system, registered during the operation of the electric motor with one pair of poles of the excitation winding. Supply flow to the mud pump was maintained manually at 40 l/sec.

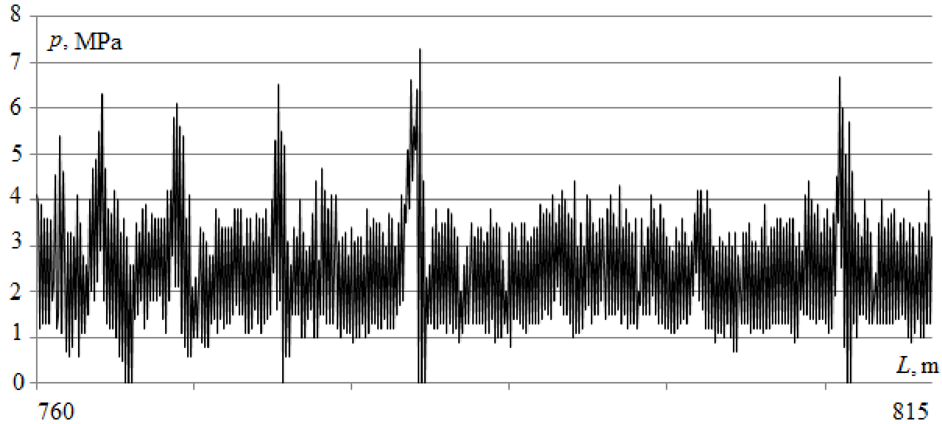

Figure 3. The discharge pressure curve at the pump discharge during drilling of well No. 20782 at 760-815 m interval.

Calculations showed that the malfunction of one polar pair of excitation coils leads to a decrease in the magnetic flux in gaps, and an increase in the rotational speed. This could lead to motor overload and pressure surges at pump discharge. Figure 3 shows pressure surges at six points of the operational drilling rig, 5.3, 6.2, 6.05, 6.35, 7.2, and 6.8 MPa, respectively. Motor shaft power *P* is directly proportional to the product of supply flow *Q* and pressure *p*, and inversely proportional to efficiency $\eta_{n.}$ of the mud pump [9]

$$P=(Q\cdot p)/\eta_{n.} \tag{1}$$

The results of power calculations at peak pressures are summarized in Table 1 below.

Table 1. Results of power calculations at peak pressures.

Pressure *p*, MPa	Power *P*, kW
5.3	265
6.2	310
6.05	302.5
6.35	317.5
7.2	360
6.8	340

Model analysis showed that zero excitation current in one pair of polar coils leads to a decrease of electromagnetic torque and power by 54%. In the actual drilling rig, the motor working with one pair of polar excitation coils leads to a decrease of motor power to 257.6 kW. At the same time, Table 1 shows that load surges lead to overloading of the electric motor. Therefore, at this point, the speed of the motor should be decreased, in order to maintain the power.

Figure 4 shows changes in the operational parameters of the mud pump, obtained using the model with one non-functional pair of polar excitation coils.

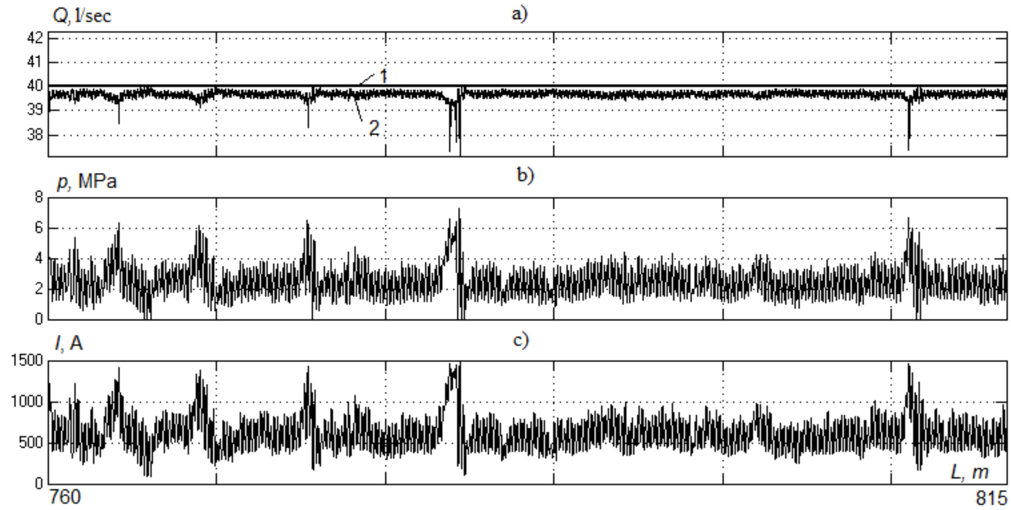

Figure 4. Results of modeling during the drilling of well
No. 20782 at 760-815 m interval.
a) supply flow, l/sec (liters per second) 1 – set supply flow, 2 – actual supply flow;
b) pressure; c) armature current

As can be seen from Figure 4, the armature current, during pressure surges, exceeds the nominal value of 1370 A, and reaches 1500 A, and the actual supply flow of the mud pump is lower than the set value. Therefore, let us introduced additional amplification factors for current and speed feedback circuits, which allowed for limiting the armature current. Figure 5 shows the results of the modeling with introduced current and speed amplification factors.

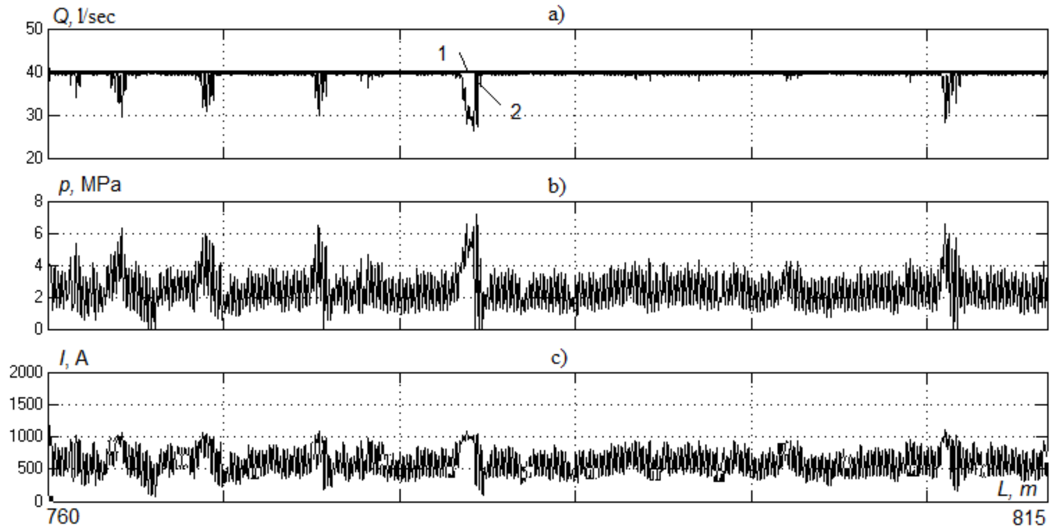

Figure 5. Results of modeling during the drilling of the well
No. 20782 at 760- 815 m interval with
current and speed amplification factors;
a) supply flow, 1 – set supply flow, 2 – actual supply flow; b) pressure; c) armature
current

In order to decrease the current, the authors introduced units Amplification factor 1 and Amplification factor 2 into the electric drive model shown in Figure 1. Modeling with current and speed amplification factors showed that the armature current could be limited, at the nominal level, by decreasing the rotation frequency, and the actual supply flow is almost equal to the set value. These amplification factors were introduced to the working equipment via the automatic control system of the thyristor converter [10], which allowed for completing the drilling without having to shut down the electric motor.

4. Organization of automatic switching of excitation coils

Failure of one of excitation coils on the drilling rig required the manual switchover of the windings. This led to delays in the operations, due to transportation of operating personnel and due to the performance of the works required for switching of the windings. Therefore, it is relevant to automate the process of winding switchover. Figure 6 shows the diagram of the device for automatic switching of the excitation windings and auxiliary winding of the DC motor with independent excitation [11].

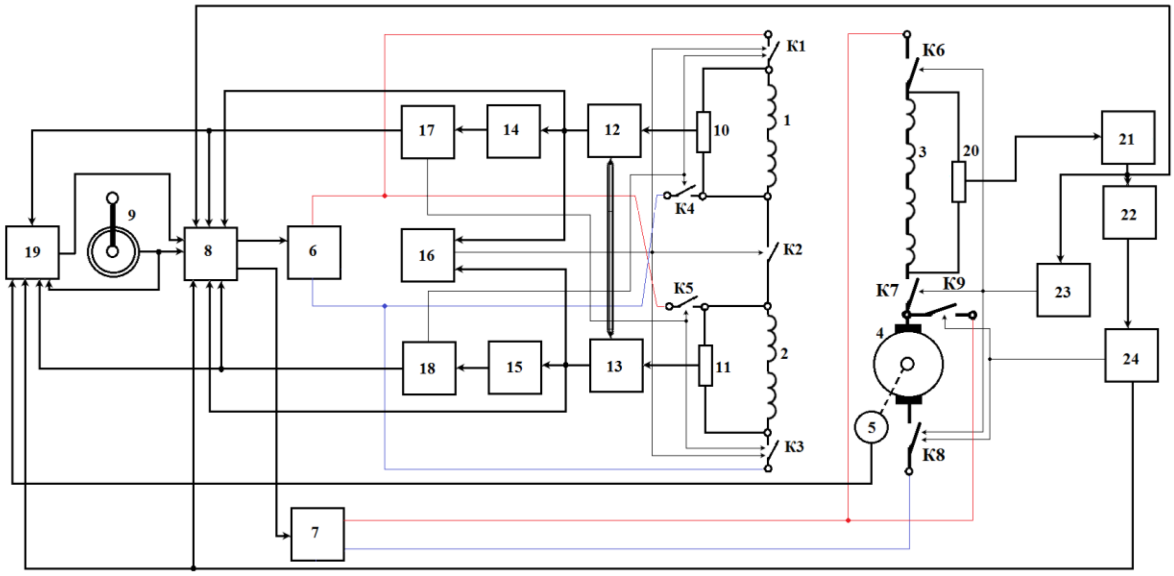

Figure 6. The device for switching between excitation windings and auxiliary winding of the DC motor with independent excitation

Functions of the device: detection of fault (short circuit) in the excitation circuit; disconnection of the excitation windings from the power supply; connection of operational excitation windings with timed delay to the power supply using the new circuit; generation of the control signal for acceleration of the motor to the set value.

In the normal mode, switches K1, K2, K3, K6, K7 and K8 are closed, and switches K4, K5 and K9 are open.

Short circuit in the excitation winding 1 (or 2) is detected by the detectors 10 (or 11) and the minimum voltage monitoring unit 12 (or 13). The output signal of unit 12 (or 3) is passed through the automatic control system 8, locks thyristor converters 6 and 7, and the executive unit 16 opens switches K1, K2 and K3, completely disconnecting the excitation windings 1 and 2. At this point, the electric drive continues mechanical rotation in the run-out mode.

Connection of the excitation windings into the new circuit is carried out by a signal from the minimal voltage unit 12 (13) via timer 14 (15) and executive unit 17 (18), which, after delay t1 (t2), closes switches K3 and K5 (K1 and K4), and connects the excitation winding 2 (1).

After connection of the excitation windings, the executive unit 17 (18) sends a signal to task generation unit 19. Unit 19 compares the signals from command unit 9 (speed setting signal, sent before the short circuit), and speed sensor 5 signal. In accordance with the set speed and its actual value, unit 19 generates the task for the automatic control system 8, for the acceleration of the motor out of the run-out operation to the set speed.

In addition to the described functions, this device also facilitates disconnection of auxiliary armature winding, in case of short circuit, as well as the restoration of operation of the electric drive after the switchover.

5. Conclusions

Research, conducted on the virtual model and the actual equipment, showed the possibility of maintaining mud pump operations in case of partial malfunction of the DC drive excitation system. The mud pump operation can be successfully maintained by the introduction of speed and current amplification factors into the feedback circuit in the automatic mode.

The authors have developed the device for detection of excitation winding malfunction and automatic switching of DC motor windings into the emergency control mode, which allows for maintaining operation of the electric drive and thus avoiding long outages of the mud pump, due to the replacement of the electric motor. In addition, it allows automating the switchover of the motor windings, in case of malfunctions, without having to stop the motor.

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