Modelling of electric drive of vibration exciter

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Abstract. The authors investigate whether it is possible to improve the models of the electric drives of vibration sources using Matrix Laboratory Simulink. The test subject is the simulation model of the electric drive of a borehole vibration exciter based on a linear double-acting electromagnetic machine. The simulation model consists of the power and control subsystem of the electric drive. This model allows the wide-range parametric analysis of processes in the electric drive by the computer modelling methods. The oscillograms of voltages and currents are obtained in the case of the electric drive control by the piston position for real-life and ideal sources of power supply. The oscillograms are compared, and the calculation error is estimated.

1. Introduction

Oil recovery is commonly enhanced through vibrowave treatment of reservoirs using surface or borehole vibration exciters [1–3].

Deep-borehole exciters with electromagnetic pulse drives greatly intensify the impact effect in the casing string at the level of the bottom-hole zone and enhance oil recovery [4–8].

If boreholes are deep, the electromagnetic pulse drives need to be diminished radially to fit with the borehole diameter. At the same time, the energy can be increased through enlargement of the linear size of the tool.

Figure 1 shows the design of the vibration exciter with the electric drive constructed as a double-acting electromagnetic machine [9].

The electric drive has a two-coil system that consists of the idle path coil 1 and the working path coil 2 inside the flux guides 3 and 4. The flux guides are connected through the intermediate member 5. The coils provide the reciprocated motion of the impact piston 6. The piston moves under the action of electromagnetic forces and hits the rod 7 of the heavy load element 8.

The piston is moved upward by the electromagnetic force of the idle path coil 1 and decelerated by gravity or stopped by the bump stop 9. The switch of the impact block coils is controlled by the inductive pick-ups 10 and 11 arranged at the top and at the bottom of the electric drive. The piston acquires the required kinetic energy from two unidirectional voltage pulses fed to the coils within a single working cycle. The fed of the control voltage pulses to the coils is strictly synchronized with the piston position coordinate.
The electromagnetic coils are controlled by the power supply and control unit depicted in figure 2. The power supply and control unit contains the three-phase reducing transformer \( T1 \), the three-phase rectifier bridge \( RB1 \), the control block \( CB \) for the electromagnetic idle path coil \( L1 \) and the working path coil \( L2 \), the thyristor switches \( TS1 \) and \( TS2 \), and the inductive pick-ups \( IS1 \) and \( IS2 \) of the top and bottom positions of the piston. The electric drive of the exciter is actuated by the signal of the switch \( KM1 \). The coils are powered by unipolar voltage pulses of the required amplitude and duration. The reciprocating motion of the piston is provided by the alternate coupling of the coils with a voltage source through the thyristor rectifier.

**Figure 1.** Design of vibration exciter

**Figure 2.** Block-diagram of the power supply and control unit

Testing of the vibration exciter (Figure 1) revealed the deficiency of a suitable approach to the optimization of its operation because of the limited power and control. The limitations are caused by inaccuracy of the commutation of the current circuits of the electromagnetic coils possessing excessive energy of the magnetic field during the switching process.

The authors suggest to expand the technical capabilities and improve the quality of the research by taking advantage of the modelling in Matlab Simulink based on numerical methods [10–15].

The authors aim to create a computer model of the power supply and control block for the electric drive of the vibration exciter (Figure 1) to implement the highly capable parametric analysis of the system in Matlab Simulink.
2. Methods and means

The simulation model assumes that the supply and control unit is a real-life power circuit with internal resistance. The source supplies the constant voltage only in the absence of the current in the load circuit. The piston position controls the feed of the voltage pulses to the coils and the duration of the pulses.

A version of the vibration exciter simulation model created in Matlab Simulink is demonstrated in figure 3.

![Simulation Model Diagram]

**Figure 3.** Version of the simulation model of the vibration exciter in Matlab Simulink

The model in figure 3 is divided into electric, magnetic and mechanical subsystems.

The Electric Subsystem includes the Three-Phase Voltage Source, the Universal Bridge and the controls of the idle path coil (Control block_1) and the working path coil (Control block_2). At the outlets of the control blocks, unidirectional voltage pulses are generated by signals from the pick-ups of the piston position.

The Magnetic Subsystem describes the electrical equilibrium and nonlinear properties of the electromagnetic machine. The input signals of the subsystem are the supply currents of the electromagnetic coils (Qut1, Qut2) and the electromagnetic force acting on the piston (Qut3). This subsystem uses the mechanisms of forced commutation of the power switches by the signals from the control blocks.

The Mechanical Subsystem in Figure 3 is implemented in accordance with the equation of mechanical motion of the electric drive.
The input variable is the electromagnetic force, and the output variables are the piston position (Coordinate_X) and the air gaps (Delta_1, Delta_2) in the idle path and working path coils.

The output variables are evaluated and recorded by the block Calculation with multichannel outlets to the virtual signal receiver Scope (Figure 3).

The supply and control subsystems are considered below.

The magnetic and electromagnetic subsystems of the electromagnetic machine are connected by the equations of the electric equilibrium for the idle path and working path coils:

\[
\begin{align*}
    u_q(t) &= i_1 r_1 + \frac{d\psi_1(i_1, x)}{dt}; \\
    u_q(t) &= i_2 r_2 + \frac{d\psi_2(i_2, x)}{dt},
\end{align*}
\]

where \( u_q(t) \) is the voltage at the bridge output in off-loading; \( r_s \) is the internal resistance of the secondary circuits of the power supply source; \( r_1, r_2 \) are the coil resistances; \( i_1, i_2 \) are the instantaneous currents in the power circuits in the coils; \( \psi_1(i_1, x), \psi_2(i_2, x) \) are the flux linkages of the idle path and working path coils depending on the currents \( i_1, i_2 \) and the piston position \( x \).

The left-hand side of the system of equations (1) contains the voltage applied to the coils. The resultant voltage will decrease with the increasing current in the power circuits of the coils.

Evidently, in the ideal case at \( r_s = 0 \), the voltage on the coils conforms with the voltage at the output of the three-phase bridge.

The control in the vibration exciter model is implemented using the control blocks (Fig. 3) of the idle path coil (Control block_1) and the working path coil (Control block_2). The piston coordinate sets the interval and duration of the voltage pulses applied to the coils. The straight-line diagrams of the control blocks are shown in Figures 4 and 5, respectively.

![Figure 4](image-url)
The output signals of the control block for the idle path coil (Figure 4) are the voltage applied to the coil (Coil voltage_1) and the control pulses of the forced commutation of the power switches (Source voltage_1).

The left-hand side of (1) is implemented in the control block (Figure 4) using the inverse back coupling. Hence, the power supply can be considered as the real-life electric energy source with the internal resistance and outlet voltage controlled by the load current.

One of the input signals of the control block (Figure 3) is the coordinate of the piston position (Coordinate_X). The signal is fed to a differentiating element (Figure 4), which makes it possible to determine the piston velocity at this element outlet and the derivative sign points in the piston direction. When the sign is positive, the piston moves towards the idle path coil. When the sign is negative, the piston moves towards the working path coil.

The sign change of the piston velocity means that the piston stops at one of the motion limits. The piston position controls the voltage on the coil. The control signal is the value of the air gap (Δ_1) at the inlet of Control block_1 (Figure 4). The control system automatically traces the piston coordinate. The simplest control uses switches for input signals of voltage from the power supply source by commands sent to the middle inlet (Figure 4). When the signal at the outlet of the switches exceeds a preset threshold, the signal is fed from the first top inlet. If the commanding signal from outlet of the switches is lower than the threshold, the signal is sent from the second bottom inlet. For Switch_1 and Switch_3, the common commanding signal is the sign of the piston velocity. For Switch_2 and Switch_4, the commanding signal is the value of the air gap in the idle path coil.

The same control mechanism with two switches Switch_1 and Switch_2 is implemented in the working path coil (Control block_2) (Figure 5).

3. Results and Discussion

Figures 6 and 7 present the oscillograms of voltages on the coils under control by the piston position coordinate using the simulation model (Figure 3). The oscillograms in figure 6 show the coil voltages with resistance in the secondary power circuits for the cases of \( r_1/r_1 = 0.47 \) and \( r_1/r_2 = 0.385 \). Figure 7 demonstrates the similar oscillograms without regard to the resistance in the secondary power circuits.
Figure 7. Oscillograms of the voltages on the coils with an ideal power source \( (r_s = 0) \)

Figure 8. Oscillograms of the currents in the coils with a real-life power source

Figure 9. Oscillograms of the currents in the coils with an ideal power source

Figure 8 and 9 demonstrate the oscillograms of currents in the coils for a real-life source \( (r_s \neq 0) \) and an ideal source \( (r_s = 0) \) of the power supply. The quantitative and qualitative changes in the behavior of currents can be seen from these figures. If a power source is ideal, the currents are overestimated by 1.1...1.34 times. The calculated parameters of the electromagnetic force, piston velocity, impact energy and frequency, electromagnetic drive capacity become overestimated too.

4. Conclusion
The computer model of the power and control subsystem for the simulation of the electric drive based on the double-acting electromagnetic machine has been developed. It provides the large-scale parametric analysis of the operation of the vibration exciter by the methods of structural modelling in Simulink.

The feature of the power source model is the dependency relation between the voltage and load current in the coils of the electromagnetic machines. It is shown that without regard to the found voltage–load current dependence, the vibration exciter model overestimates design parameters.

The modelling has demonstrated that at the ratio of the resistance in the secondary power circuits to the load resistances of \( r_s/r \approx 0.385 ... 0.47 \) the estimated values of instantaneous current in the electromagnetic coils of the electric drive can differ by 1.1...1.34 times.

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