Simulation of an adjustable synchronous electric motor drive of a pumping unit in a reservoir pressure maintenance system

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Abstract. The paper describes the method of controlling water supply while maintaining reservoir pressure via changing the speed of rotation of a pumping unit synchronous electric motor drive. The paper presents a review of existing frequency converters, specifying their advantages and disadvantages. The selection of a cascade semiconductor frequency converter is substantiated. A detailed description of the computer model of an adjustable drive system based on a high-voltage synchronous electric motor drive and the selected frequency converter is also presented. The results of modeling in the form of graphs of transients allow us to conclude about the adequacy of the model and the possibility of its practical use in the study of transient modes of controlled electric pumping units based on synchronous motors.

1. Introduction

Currently, automated reservoir pressure maintenance systems are used during oil production. Reservoir pressure control therein is carried out by means of water injection into the reservoir. Water is fed into the reservoir using via modular water injection stations, equipped with synchronous and asynchronous electric motors of high capacity. The latter, as a rule, are powered directly from a 6 or 10 kV high-voltage power network [1]. Despite variety of advantages of synchronous electric motors, their rotation speed control, until recently, was associated with a number of difficulties [2]. In connection therewith, water supply controlling is usually carried out by throttling or bypassing method, thus it appears rather costly. This paper deals with a computer model of an adjustable drive system based on a high-voltage synchronous electric motor drive and a semiconductor frequency converter.

2. Analysis of the simulation object

As a simulation object, let us consider the electric motor drive of the TsNS-120-1775-3T-M pumping unit with rated capacity of 120 m³/h and with a head of 1775 m. This pumping unit is driven by a 1600-kW STDM-1600-2RUHL4 synchronous electric motor with rated rotation speed of 3000 rpm. The motor is powered directly from the 6 kV, 50 Hz power network. Currently, the electric motor drive speed is not controlled, the start is performed under an asynchronous mode followed by voltage supply to the excitation winding when the drive reaches the subsynchronous speed. The motor field is controlled by means of a static thyristor exciter of VTE 10-315/150-02-UHL4 type with a digital control system. The pressure control in the reservoir is carried out via flow throttling with a valve, installed on the pressure pipeline. As is known, this method for control is not cost-efficient, wherein, the wider the speed control range, the greater the loss of energy.

There are various variants to implement semiconductor converters applicable in this case [3]. In
particular, there are two-transformer converters based on current inverters, for example, domestic converters of FCCS series [4], the structure of which corresponds to the one shown in Fig. 1. The disadvantage of this circuit resides in high cost and dimensions of the filtering elements and the transformer, especially one, installed at the outlet of the inverter, a limited range of speed control due to the fact that the output transformer is able to convert the voltage to a specified frequency value only, poor efficiency due to multiple energy conversion. The advantage resides in the relative simplicity and low cost of a semiconductor converter.

![Figure 1](image1.png)

**Figure 1.** Frequency converter according to two-transformer circuit, T1 - step-down transformer, VS1 - controlled rectifier, VS2 – stand-alone current inverter, F – sin-wave filter, T2 - step-up transformer, M - motor.

Another embodiment of converter includes the converters according to the circuit of a 12-pulse rectifier – a three-level stand-alone voltage inverter based on lockable thyristors, for example, frequency converters of the Sinamics series by Siemens (Fig. 2). The advantage of such converters involves relative simplicity and reliability of the circuit, due to the use of power thyristors. The disadvantage resides in non-sinusoidal output currents, due to the relatively low switching frequency of the thyristors, as a rule, not exceeding a few kHz [5].

![Figure 2](image2.png)

**Figure 2.** High-voltage frequency converter of the Sinamics series, T — transformer, VD1, VD2 - three-phase uncontrolled rectifiers, VS - three-level stand-alone voltage inverter based on lockable thyristors, M - motor.

The most advanced are frequency converters according to the circuit of cascade frequency converters [6], exemplified by Perfect Harmony Siemens converters. The advantage of such converters resides in sinusoidal output currents, due to the high switching frequency of low-voltage transistors or thyristors of cells and a multi-level system for currents generation in case of series connection of converting cells. The disadvantage of such converters involves relatively high cost and complexity of the control system.
Having analyzed the advantages and disadvantages of the converters under consideration, the third variant, referring to the cascade converter, can be recognized as the most advantageous for the considered electric motor drive system.

3. Simulation result

The model of a synchronous motor, taking into account a number of assumptions, can be represented by the following set of equations in the form according to Kosh [7, 8]. The equations are recorded in a rotating coordinate system $d$-$q$, oriented along the rotor field.

EMF equation of the stator winding along the $d$ axis:

$$L_d \frac{di_d}{dt} = U_d - R_d i_d + \omega L_q i_q,$$

(1)

where $U_d$ is the stator voltage component along the $d$ axis, V; $L_d$, $L_q$ is the inductance of the rotor winding along the $d$, $q$ axis, Hn; $i_d$, $i_q$ is the stator current component along the $d$, $q$ axis, A; $R_d$ is the stator copper resistance, Ohm; $\omega$ – is the rotor spinning speed, rad/s.

An EMF equation of the stator winding along the $q$ axis:

$$L_q \frac{di_q}{dt} = U_q - R_q i_q - \omega L_q i_q - \psi_r \omega,$$

(2)

where $U_q$ is the stator voltage component along the $q$ axis, V; $\psi_r$ is the excitation flow, Wb.

An EMF equation of the rotor winding:

$$L_r \frac{di_r}{dt} = U_r - R_r i_r,$$

(3)

where $U_r$ is the excitation voltage, Lr is the excitation winding inductance, Hn; $R_r$ is the rotor copper resistance, Ohm; $i_r$ is the excitation current, A.

An equation for torque:

$$M = \frac{3}{2} p [\psi_r i_q - (L_d - L_q) i_d i_q],$$

(4)
where $p$ is the number of pairs of poles.

Equation for the mechanical part of the drive:

$$J \frac{d\omega}{dt} = M - M_c,$$

where $J$ is the equivalent moment of inertia of the rotor, kg m$^2$; $M_c$ is the moment of resistance to movement.

It is worth noting that the above set of equations (1) - (5) does not take into account the presence of damping windings, and also assumes the steady-state value of the magnetic flux, generated by the excitation winding, and does not take into account the influence on it caused by the rotor windings. These assumptions, according to the authors, can be considered insignificant for frequency-controlled drives.

The model, corresponding to equations (1) - (5) and implemented in xcos graphic simulation system, built into the scilab system, has the form (Fig. 4).

**Figure 4.** Model of synchronous motor.

Taking into account the short time of transient-processes in the frequency converter compared to electrical and mechanical time constants of the motor and pumping unit, and also accounting for the fact that the cascade frequency converter current is virtually sinusoidal, its simplified linearized model was used during simulation (Fig. 5).
Figure 5. Simplified linearized model of the frequency converter.

The electric motor drive control system comprises the following controllers (see Fig. 6), from top to bottom: the current controller of the magnetizing stator current component, having a zero setting point, since the motor field is implemented by means of independent winding on the rotor, the speed control circuit with its subordinate circuit of torque-generating stator current component and excitation flux control circuit. Current controllers are set to technical optimum, and speed and flow controllers are set to symmetric optimum according to the methods known from the state of art.

Figure 6. Block of controllers.

The load model, in accordance with the laws of similarity for centrifugal machines, has the form of a quadratic dependence of the torque, generated by the centrifugal machine, on speed and a quadratic dependence of pressure in the pressure pipeline on speed:

\[
M_c = K_1 \omega^2, \quad K_1 = \frac{M_{\text{nom}}}{\omega_{\text{nom}}^2},
\]

\[
p = K_2 \omega^2, \quad K_2 = \frac{p_{\text{nom}}}{\omega_{\text{nom}}^2},
\]

where \(M_{\text{nom}}\), \(\omega_{\text{nom}}\), \(p_{\text{nom}}\) are nominal values of the torque (N·m), the rotor speed of rotation (rad·s) and pressure (Pa), respectively.

The proportionality factors in these equations depend on the state of the valve and the equivalent friction of piping and the reservoir and vary step-wise during simulation.
The general model of the electric motor drive, including the previously described blocks, is shown in figure 8. In addition to these blocks, the model comprises a pressure controller in the pipeline, set to a symmetrical optimum, and the controllers’ operation control units. According to the established algorithm, firstly a smooth acceleration of the drive to the nominal speed occurs when the pressure controller is switched off and the valve on the pressure pipeline is closed. Then the valve opening follows. And only after that the pressure controller is triggered. The selection of this type of a start-up algorithm is caused by the fact that when the pump is switched off, there is a significant residual fluid pressure in the reservoir, and putting the controller into operation before the drive starts to operate under its nominal operation mode could result to an emergency operation mode of the pump.

Fig. 9, 10, 11 present the simulation results.
Figure 9. Diagrams of variation in speed.

Figure 10. Diagrams of pressure variation in the pipeline.

Figure 11. Diagrams of pressure variation in the pipeline.
4. Conclusion
Within the first 3 seconds there is a smooth acceleration of the motor to the nominal speed of rotation while the valve is closed. At the 6th second, the valve opens, resulting to the load increase on the drive, while the speed remains unchanged. The pressure controller at this stage remains switched off, and the pressure control system is open-circuited. At the moment of 9.25 s, the pressure control system is activated and the speed of rotation decreases. The pressure in this case decreases to the specified value. At the moment of 12.5 s, the setting point for the drive changes, which results in a greater decrease in speed and, consequently, in pressure within the pipeline. The diagrams show that the controllers’ calculation is performed correctly, and the proposed computer model of the electric motor drive appropriately implements the simulation of the pumping unit adjustable electric motor drive system operation.

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