Engineering model of the electric drives of separation device for simulation of automatic control systems of reactive power compensation by means of serially connected capacitors

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Abstract. It is developed a mathematical model for an electric drive of high-speed separation device in terms of the modeling dynamic systems Simulink, MATLAB. The model is focused on the study of the automatic control systems of the power factor (Cosφ) of an actuator by compensating the reactive component of the total power by switching a capacitor bank in series with the actuator. The model is based on the methodology of the structural modeling of dynamic processes.

1. Introduction
As is known the energy efficiency of the multi-motor synchronous hysteretic electric drive of separation device is defined as the ratio of the active power \( P \) (which performs the mechanical work) to the total (apparent) power \( S = \sqrt{P^2 + Q^2} \) that leads to the relation as follows \( \text{Cos}\phi = P/S \). Here \( P = UI \text{Cos}\phi \), \( \phi \) is the phase shift between the voltage \( V \) and the current \( I \) in an AC circuit, and \( Q = UI \text{Sin}\phi \) is the reactive power creates the electromagnetic field in a windings of an electric motor. The reactive power does not perform the useful work and additionally loads the power circuit.

The more power is, the less \( \text{Cos}\phi \) takes place, and the more energy is lost in distribution systems, generators and other equipment of the power system. Also is well-known that the widely used in industry \( \text{Cos}\phi \) is equal to 0.9 – 0.95.

Compensation of the reactive power in an electric drive of the separation device, which today are considered as the most advanced technology leads to a real possibility to reduce the cost of electricity supplying by nuclear power plants [1].

2. Statement of the problem
The synchronous hysteresis electric drives (HED) of high speed separation devices connected in parallel is powered by a static frequency converter (SFC), forming a grid "HED-SFC" with the non-standard frequency power and the low enough \( \text{Cos}\phi \) (power factor, PF) = 0.2 – 0.3 [2].

The increase in a PF is possible as by means of the traditional inclusion of capacitors for compensation of the reactive power of HED connected in parallel [2] or in series with the HED [3] (figure 1a). The sequential capacitive compensation of the resonant frequency \( R-L-C \) circuit is not
dependent on the active resistance $R$ and significantly reduced the voltage $U$ at the output of the frequency converter (FC) ensuring the nominal value of the voltage $U_s$ for the separation device. The initial task for the manual or automatic control of PF in the power system as a function of setting up the serial power loop $L-R-C$ for a frequency close to the resonance $f_0$ by means of the capacitance change is stabilization of the nominal voltage supply of $U_s$ of the actuator by the change of the output signal $U_s$ of a FC. Only in this way it is possible to identify the resonant (static) characteristics of the dependence of the voltage on the capacity $U(C)$ in the HED-SFC grid in the $\{U; C\}$ coordinate space.

3. The construction of the model
To make simulation the energy system separation device- frequency converter (GC-FC) as the control object the structure presented in figure 1a is transformed into a dynamic system shown in figure 1b acceptable for presentation in the terms of the automatic control theory and the Simulink Toolbox of MATLAB [4] as follows:

![Diagram](image)

**Figure 1.** Compensation of the reactive component of the total power of HED in a case of the series configuration of capacitors $C$: $L-R$ are the inductance and Ohmic resistance of the parallel-connected HED; 1a is the wiring diagram; 1b is the structural dynamic model; 1/R are the blocks of integration, the $p$ is the Laplace operator.

In the structure of figure 1a the capacitor $C$ has a charge calculated as $q = \int i dt$, where $i$ is the current in the circuit and the voltage on the capacitor is equal to $U_c = q / C$. The supply voltage $U_s$ defined as $U_s = U - U_c$ is the sum of the voltages where $U_L$ is related to the inductor $L$ and $U_R$ corresponds to the resistor $R$. If $U_R = iR$ is subtracted from $U_c$ (the right adder in figure 1b), the voltage on inductance $L$ is remains. The latter determines the flux linkage $\psi = \int U_c(t) dt$ which in turn generates the current $i(t) = \psi(t) \frac{1}{L}$ or in another form of writing $U_L = L \frac{di}{dt}$ [4]. The transfer function
model for the channel input of the voltage $U$ at the output SFC, the output voltage $U_s$ is

$$W(p) = \frac{U(p)}{U_s(p)} = \frac{R(t) p L / C + 1 p C}{T^2 p^2 + 2 \xi T p + 1}$$

where $T = \sqrt{L/C}$ is the time constant, $\xi = RC / 2L$ is the rate of oscillation, $p$ is the Laplace operator.

### 4. Model system in the terms of the Simulink Toolbox of MATLAB

Organization of the automatic control processes using the alternative current and their modeling in terms of the Simulink, MATLAB Toolbox requires the introduction of the high-frequency variables $U$ and $U_s$ (see figure 1a) which are proportional to their amplitude values, for example by means of the full wave rectification with following filtration (see blocks, "Abs", “Transfer Fcn” [5]). Control of exposure and changes of parameter are executed by the multiplying devices (see block «Product» [5]), one input of which receives the value of a parameter, and other deals with control action.

Then the engineering model of the electric drive of GCs for the purposes to control the power factor has the form shown in figure 2, where to be more definite the following parameters are specified: the supply frequency $f_0 = 1800$ Hz ($\omega_0 = 11280$ s$^{-1}$), $U_0 = 380$ V, and the aggregate of GCs connected in parallel has the resulting parameters: $L = 50$ $\mu$H, $R = 0.15$ $\Omega$ and $C_0 = 157$ $\mu$F corresponding to the resonance $R-L-C$ circuit. Under these conditions $\cos \varphi \sim 0.25$ and the quality factor $Q \sim 3.8$.

![Figure 2. The engineering model of HED for the sequential reactive power compensation in conjunction with the system of automatic stabilization the $U_s$ voltage for supplying HED in the terms of the Simulink Toolbox of MATLAB. Here “Slider Gain3” corresponds to $1/L$, “Slider Gain1” matches $1/C$, and “Slider Gain” meets $R$.](image-url)

The structure of figure 1a is represented by the lower part of figure 2. It includes the blocks "Slider Gain". The feature of the "Slider Gain" block is its ability to visualize the adjustable parameters of the $L-R-C$ circuit and to make the “online” changes them in the process of the computing code execution by computer simulation [5].

The automatic stabilization of the $U_s$ voltage (the upper part of figure 2) is performed by the control circuit consisting of special means to measure the high-frequency variables $U$, $U_s$, (detecting takes place in the block "Abs1"; filtration is realized in the block "Transfer Fcn3"; 6" and the block "Slider Gain4" is intends to adjust an exact match of the unbent values of $|U_s|$, $|U|$ to their amplitude values);as well as the block for comparison “Constant" ($U_{spec} = 380$ V) and $|U_s(t)|$, the block of integration “Integrator2” with the transfer coefficient $k = 0.02$ (“Gain6”) and the model of the manged SFC on the basis of the multiplication unit (“Product”). The control signal is given to one of the inputs
of the “Product” block and on the other is set the harmonic signal (“Sine Wave”) with a frequency of \( \omega_0 \) and amplitude, which value is wittingly greater than \( U_s/Q \). The time-to-steady-state operation in the system of the \( U_s \) voltage stabilization in this case under consideration is equal to \( t \sim 0.3 \) s.

The static characteristics of the power resonant circuit when changing the \( L-R \) parameters of are determined at slow (relatively to the performance of the stabilization system of the \( U_s \)) change the parameter \( 1/C \) in the range \((0.8 – 1.2) / C_0\), where \( C_0 = 157 \mu F \) is the “resonant” value of the capacitance \( C \) of the capacitor bank at normal condition of the GC separation cascade. The capacitance variation \((0.8 – 1.2) / C_0\) corresponds to the change of \( C \) within the range \((196 – 131) \mu F \). The change in the magnitude of \( 1/C \) is carried out as multiplication of the \( 1/C \) value on the variable transmission coefficient of the managed block “Product”. Is The signal from the “Integrator1” goes to one input of the “Product” block, and the other receive a periodic linearly varying signal from the “Repeting Sequence2” block with the settings of the output changes from “0.8 to 1.2” for the period of time \( T = 5 \) s. The display changes to \(|U|(1/C)\) is executed by the “XY Graf” block.

The external time of calculation of the structure presented in figure 3 using the PC is equal to a few minutes In the process of simulation by a computer it is possible every 5 “machine” seconds make drastically changes of the \( R-L \) parameters, corresponding to the change of the electrical parameters of a HED e from their nominal values of "on line" by means of setting in the blocks "Slider Gain”and "Slider Gain4".

The static (resonance) characteristics of the power oscillation circuit shown in figure 1a correspond to the serial connection of the capacitor \( C \) and automatically stabilized supply voltage \( U_s = 380 \) V presented in figure 3.

![XY Graph](image)

**Figure 3.** The resonance (static) characteristics of \( U(1/C) \) and \( U(C) \) for the aggregate of GCs when changing the number of GCs at \( \pm 10\% \). The nominal number of the GCs in an aggregate corresponds to the curve in the center of the figure. The minimum of \( \frac{dU}{dC} = 0 \) corresponds to \( \text{Cos} \phi = 1 \). The workspace for the values of \( \text{Cos} \phi < 1 \) is to the right of the local extrema.
Conclusion
1. The model of the electric-drive of high-speed separation device for isotope separation with the serial capacitive compensation of the reactive component of the total power in terms of the Simulink Toolbox of MATLAB as the extreme dependence of the output voltage $U$ at the cleats terminals of SFC from the capacitance $C$ is developed.

2. It is shown that the energy efficiency $\cos \varphi =1$ for the power system "HD-FSC" is achieved in the state of the resonance for the power oscillating circuit included the compensating capacitance $C$ with the inductance – active parameters of the electric-drive. The nominal voltage $U_i$ for the power supply of the electric-drives of GCs is automatically stabilized when the output voltage FSC is equal to $U = U_s/Q$, where $Q$ is the quality factor power resonant circuit.

3. The model allows to reflect the technological changes of the electrical parameters of the local power system "HED-FSC" with sequential compensation of the reactive component of the total power in the restructuring of the assembly of GCs and the drift of their parameters of the electric drives.

4. The build model is based on the methodology of the structural modeling of dynamic processes in electric circuits.

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