Adaptive system model of stabilization of the power factor of actuators of centrifuges for uranium enrichment with structural dynamic model of electric drive with parallel reactive power compensation

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Abstract. Presents an engineering model of adaptive system of automatic stabilization of the power factor Cos φ = 1 as the condition of resonance at the frequency of power supply with parallel compensation of reactive power of electric drive of centrifuges battery of capacitors. The resonance in the power circuit corresponds to an extremum (minimum) of total current was taken as the goal of the algorithm automatic search. The operation of the adaptive control system in conjunction with a structural dynamic model of the object of optimization is presented modeling in terms of a Simulink (MATLAB). It is shown that in the process of automatic stabilization Cos φ = 1 excluded “overcompensation” in the local electric power network, including when disconnect blocs of the centrifuges. The adaptive control system is insensitive to additive errors of the sensor current I, can be realized general technical means and applied in general power networks.

1. Introduction
It is known that the energy efficiency of the electric drive is characterized by a power factor Cos φ = P/S, where S = \(\sqrt{P^2 + Q^2}\) the total power, \(P = UI \cos \phi\) - active power, \(Q = VI \sin \phi\) is the reactive power creates the electromagnetic field in the windings of the electric drive. Reactive power performs no useful work, additionally load chains power transmission, compelling to increase the size and power of generating devices.

Reactive power compensation in electrical power circuits is a significant economic factor [1] separation of isotopes of uranium high-speed gas centrifuges with driven on the basis of the hysteresis motors /HM/ with power factor Cos \(\phi = (0.2 – 0.4)\). HM is powered from static frequency Converter /SFC/ forming a local grid "HM – SFC" with non-standard frequency of the power network [2]. The increase in the power factor Cos \(\phi\) in the energy system is enabling the parallel composition HMs of the compensating capacitors, which can provide a standard value Cos \(\phi = 0.9 – 0.95\). But in this case, the proportion \(I_Q\) of the reactive component of the total current \(I\) is (50–30)%.
2. Statement of problem
In [3] introduces the concept of automatic stabilization of the power factor \( \cos \varphi = 1 \) motor centrifuge, based on automatic search [5] of minimum of extreme dependence of the total current \( I \) in functions capacity \( C \) (figure 1a) corresponding to the resonance in the power circuit on the supply frequency.

Extreme characteristics \( I(C) \) in [3] are represented as inertia-free, built based on electric calculations. When changing the number of operating centrifuges and other factors affecting the inductance \( L \) and the resistance \( R \) multimotor electric drive, it is necessary analytically to re-present and tabulate new condition \( I(C) \) in the model control system presented in [3].

3. Building a structural dynamic model of the actuator with compensation
In this paper, the electric drive with parallel compensation appears to be a dynamic model constructed based on methodology of structural modeling of dynamic processes in \( L-R-C \) circuits [6]. Model can be easily represented by means of visual programming Simulink (MATLAB) with the ability to interactively change parameters of electric drive simulation. The transformation of electrical structure of figure 1a in the dynamic model figure 1b suggests SFC as the "source voltage" \( U_{sup} = 380 \) V and the ratio of the currents \( I_1, I_2 \), educated, diverse reactive impedances in the form \( I_1, + I_2 = I \) (see figure 1a A and figure 1b, the adder No. 1).

![Figure 1. The electrical circuit (a) and dynamic model (b) power system "HM– FSC" of compensation of the reactive component of the total power parallel by connection of the capacitor \( C \): \( s \) – Laplace operator, \( 1/s \) – block integration. \( L-R \) – inductance and ohmic resistance of the parallel-connected motors.](image)

In a capacitive branch of the structure of figure 1a the charge of the condenser \( q = \int I_1 dt \) (integrator \( 1/p \), figure 1b) when the voltage on the capacitor \( U_C = q/C = U_{sup} \). For \( R-L \) branch of figure. 1a, the voltage on the inductance \( U_L(t) \) determines the linkage \( -\psi(t) = \int U_L(t) dt \) (integrator \( 1/p \)) and the flux linkage – current \( I_2(t) = \psi(t) L^{-1} \) (unit is \( 1/L \)). The current \( I_2(t) \) generates a voltage drop \( U_R(t) \) on the resistance \( R \). This voltage is the output for \( R-L \) circuit and is subtracted from the input \( U_{sup} = U_C \) (adder No. 2, figure 1b) in determining the \( U_L \). Thus is manifested the internal feedback determines the development of electrical processes in \( R-L \) – chain. [6]).

Negative feedback circuit formed by the element of comparison No. 3 voltage \( U_C(t) \) \( U_{sup} = 380 \) V in conjunction with block integration \( k/p \), modify the output current \( I \) until the \( U_C(t) = U_{sup} \) [4].

The family of characteristics according to the total current \( I \) from the compensating container for the composition HM, connected in parallel with the resulting parameters \( L = 50 \mu H, R = 0.15 \Omega, \cos \varphi = 0.25 \), when the supply frequency \( f = 1800 \) Hz is shown in figure 2, where \( C = 147 \) F corresponds to the resonance \( R-L-C \) circuit in the normal condition of the cascade fits (see the curve 2).
Figure 2. The family of static characteristics $I(C)$ of the actuator with capacitive reactive power compensation: curve 2 – during normal condition of the cascade of centrifuges ($L = 50 \ \mu H, R = 0.15 \ \Omega, f = 1800 \ Hz$); curves 1/3 – when the increase/decrease in the number of centrifuges by 10%.

A symptom of power factor $\cos \varphi = 1$ of actuator accepted the minimum of $I(C)$ where $dI/dC = 0$ [3], which corresponds to the resonances of currents $R-L-C$ circuits in a specific technological conditions

The management task is solved by the use of the stepper algorithms of automatic search $dI/dC = 0$ extreme $I(C)$ [5] (figure 3).

Figure 3. The system of automatic search of the of the power factor $\cos \varphi = 1$.

4. Control law

The algorithm is based [3, 5] on the determination of the direction of movement of the search coordinates $C(t)$ to $dI/dC = 0$ the extreme dependence $I(C)$ in finite differences: $\Delta I/\Delta C_n = 0$ where $n = 1, 2, \infty$; $\Delta C_n = C_n - C_{n-1}$, where $\Delta C_n$ – amplitude search step in the interval $T$ the duration of the $n$ – th search step; $C_n, C_{n-1}$ – capacity values of $C$ at time $T_n, T_{n-1}$; $\Delta I_n = I_n - I_{n-1}$ – the increment of output of the total current $I$ in $T_n, T_{n-1}$ in the logic:

$\text{Sign } [\Delta C_n |\Delta I_n] < 0 \rightarrow (\Delta C_{n+1} > 0)$;

$\text{Sign } [\Delta C_n |\Delta I_n] > 0 \rightarrow (\Delta C_{n+1} < 0)$;

$C_{n+1} = \sum_{1}^{n} C_n$.

The algorithm is characterized by self-oscillation process is relatively $\Delta I_n/\Delta C_n = 0$. 
Figure 4. Engineering model of system of automatic stabilization of the power factor \( \cos \varphi = 1 \) of electric drive of centrifuges with capacitive parallel compensation: the upper part – the dynamic model of the drive: “Slider Gain3” correspond to \( 1/L \), “Slider Gain4” – \( R \) \( (L = 50 \ \mu F, R = 0.15 \ \Omega, f = 1800 \ \text{Hz}) \) ; “Prodact1” unit performs the operation of dividing the input variable of the unit on the capacitance \( C \); the lower part – the control algorithm.

Measurement of the total current \( I \) at the output of the model is managed \( \text{FSC} \) (“Sine Wave” together with “Prodact”) carried out by rectification (block “Abs1”) and filter the variable component “Tranfer Fcn4” with \( W(s) = 1.57/(0.012^2s+0.2s+1) \) with correction matching \( I(t) \) of the amplitude value of the high frequency variable. Value of \( I \) is automatically configured by a negative feedback loop consisting of measuring the amplitude \( |U_C| \) of the high-frequency variable \( U_C(t) \), of element comparisons \( U_{sup} = 380 \ \text{V} \) (bloc “Constant2”) and \( |U_C| \) of bloc “Integrator2” with transfer ratio \( k = 0.03 \), of the model managed FSC with setting up “Sine Wave” (\( \omega = 11309 \ \text{s}^{-1} \) ) and amplitude ”250”, more of current \( I \) in the structure of figure 1 at resonance at the frequency of the supply. Unit “Product1” implements the operation \( 1/C_{n+1} \).

The settling time of transients in the model of the actuator figure 4 is \( t = 0.2 \ \text{c} \).

Algorithm of automatic search is implemented as digital in terms of Digital Simulink with the period of quantization of discrete blocks is equal to \( T \). To work stepping algorithm for static [5] increment \( I(C) \) made of \( T = 0.2 \ \text{s} \). Magnitudes \( \Delta C_n \) and \( \Delta I_n \) are computed using elements of “Unit Delay” with transfer function \( W(z) = 1/z \), where “\( z \)” is the argument of the mathematical apparatus of analysis of digital automatic systems (“\( Z \) – transform” [7]). Control function \( C_{n+1} \) is generated by a discrete integrator \( W(z) = Tz/(z-1) \) [7]. The amplitude of search step accepted \( \Delta C_n = 3.6 \ \mu F \) (setting ”Gain” is ”-1.75 10^{-5}”). The terms of the reverse, according to the logic of the search algorithm are implemented by blocks “Produkt2” and the operator “Sign”. The initial conditions of the system operation \( C = 165 \ \mu F \) installed in integrator.

For local power “HM-FSC” the most dangerous is the factor of “overcompensation” that is associated with the disconnecting of centrifuges ((including centrifuge with enhanced performance [8]) in the restructuring of the separation of cascades and risk of transition through the state \( \cos \varphi = 1 \), causes a change in the nature of the power supply from inductive to capacitive. Figure 5 illustrates the operation of the system, included at \( C = 165 \ \mu F \) when you increased the number of centrifuges in the cascades (the extreme characteristics curve 1). The search algorithm finds the condition \( \cos \varphi = 1 \) of the energy system corresponds to the resonance at \( C = 161 \ \mu F \). At the moment \( t = 2 \ \text{s} \) restored staffing number of centrifuges (curve 2), with the exit power grid in mode “overcompensation”. Targeted search procedure
finds a new value of the resonance restoring the Cos \( \phi = 1 \) at \( C = 147 \, \mu F \). Similar situation with further reduction in the number (at time \( t \approx 4.5 \, s \)) of centrifuges, providing Cos \( \phi = 1 \) at \( C = 132 \, \mu F \).

Drift of the electrical parameters of the electric drive of centrifuge is mostly due to temperature changes of the production floor and slightly changes the magnitude \( R \) of the windings of the electric drive, which almost corresponds to the small offset \( I(C) \) on axis \( I \).

![Graph](image)

**Figure 5.** Automatic stabilization Cos \( \phi = 1 \) if you change the number of centrifuges in the cascade: curve 2 – regular, curves 1/3 – more/less 10% of the centrifuges in the cascade. Symbols correspond to the text.

In the process the self-oscillating mode of search in the neighborhood of the values \( dI/dC = 0 \) the deviation from the extremum does not exceed (1..2) \( A \) and can be reduced by choosing \( \Delta C \). In this collection of articles presents an algorithm of automatic search \( dI/dC \rightarrow 0 \) for the inductive nature of the power supply with the improved characteristics of the work.

5. **Other applications**

Adaptive search system of automatic stabilization with a structural dynamic actuator model in the vicinity of the resonant condition at the frequency of the supply current is an alternative to increase the efficiency of power factor in industrial technological systems, as well as in the autonomous /board/ with power-limited (renewable) resources.

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**Conclusion**

1. Presents a model of adaptive system of stabilization of power factor Cos \( \phi = 1 \) of the electric drive of high-speed gas centrifuges for separation of uranium isotopes with a structural model of dynamic processes in the drive with capacitive parallel compensation of the reactive component of the total power in the vicinity of the resonance frequency of the supply.

2. The system operation is based on the automatic search for extremum of the minimum of the total current \( I \) on the output terminals FSC in functions of capacity \( C \), when \( dI/dC = 0 \). Excluded state of the power system in the mode of "overcompensation". 


3. To operate the system enough measure of the total current $I$ at the terminals FSC.
4. The control algorithm is insensitive to additive errors in measurement of the total current $I$.
5. The control system can be implemented on the basis of General industrial equipment

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