Algorithm of automatic search \( \cos \phi = 1 \) for electric drive of high speed centrifuges with minimum limit cycle in region of the inductive nature of the power supply

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Abstract. System stabilization of \( \cos \phi \) is an adaptive system of automatic search in area of the resonance of power circuit, which is form by including a compensating capacitance \( C \) in parallel with the electrical drives (inductive - active load) of centrifuges. The resonance corresponds to the extremum - minimum of total current \( I \) as a function of the capacitance \( C \). The aim of working an adaptive system is ensured of automatic search \( dI / dC < 0 \) in a small neighborhood of the extremum \( I(C) \), which provides of the inductive nature of electric power. The operation of the system in a neighborhood of a given \( dI / dC < 0 \) is improved by modifying the switching conditions search impact separately for positive / negative steps. The operation of the adaptive control system was represent by simulation results in terms of Simulink (MATLAB). In the process of automatic stabilization \( \cos \phi \sim 1 \) is excluded state of “overcompensation”, the search period is reduced 2-fold relative to the classic of search procedures.

1. Introduction
It is known that the energy efficiency of the electric drive is characterized by a power factor \( \cos \phi = P/S \), where \( S = \sqrt{P^2 + Q^2} \) is the total power, \( P = UI \cos \phi \) is active power, \( Q = UI \sin \phi \) is the reactive power. Reactive power performs no useful work, additional load circuit of the power transmission and forces to increase the size and power generating devices.

Reactive power compensation of the electric drive of centrifuge separation systems is a substantial part of the to reduce the cost of electricity supplied by nuclear power plants [1].

Traditionally, the compensation of reactive component of the hysteresis motors (HM) in the local electric power network (HM – static frequency converter (SFC)) cascade high-speed centrifuge is the inclusion of capacitor bank.

2. Statement of the problem
In [2 - 4] considered the automatic stabilization system of \( \cos \phi = 1 \) for the local electric power grid "HM – SFC” as providing resonance at a frequency of power \( R-L-C \) circuit (\( L-R \) inductance / resistance of the electric drive) based on the adaptive search algorithm of minimum of the total current \( I(C) \).

In the present work is considered as the continuation of a theme [2] (see in this volume), the algorithm of high precision automatic search in a small neighborhood of the minimum of \( I(C) \) in the field of the inductive nature of the power supply.
3. Structural dynamic model of the actuator

For further discussion on figure 1 presents with brief explanations of the result of converting $R\cdot L\cdot C$ electrical circuit [5] in the structural dynamic model as an object of extreme control [6] in accordance to changes of the capacitance $C$.

![Schematic diagram](image)

**Figure 1.** Schematic diagram (a) and a structural dynamic model (b) power system "GD– SFC" with the compensation of the reactive component as part the parallel connection of the condenser $C$.

Laplace operator, $1/s$ – blocks of integration, $L\cdot R$ is inductance and active resistance of motors.

The voltage on the capacitor $U_c = q/C$, where the charge $q = \int I_c dt$ in figure 1a (or $q(s) = I_c(s)/s$ in figure 1b). For $R\cdot L$ circuit figure 1a, the voltage on the inductance $U_L(t)$ determines the flux linkage $-\psi(t) = \int U_L dt$ (or $-\psi(s) = U_L(s)/s$) and the flux linkage $\psi(t)$ is current value $I_2(t) = -\psi(t)/L$ ($I_2(s) = -\psi(s)/L$).

The current $I_2$ creates a voltage drop $U_R$ on the resistance $R$, which is subtracted from the input $U_C$ (adder No 2, figure 1b) when determining the $U_L$ [5]. Circuit negative feedback with integral control action (highlighted in dark color in Figure 1b) simulates the SFC as the "generator voltage", providing automatic stabilization $U_C = U_{man}$ due to the change of the total current $I$ [6].

4. Modified algorithm of automatic search of the minimum total current

Because of the physical discrete ($\Delta C$ is units-tens $\mu F$) of compensating capacitance change $C$ in the adaptive algorithms [2...4] applied to the stepping principle of the automatic search. When the duration $T$ of the search step $\Delta C$ more end-time transients $\Delta(t)$ in the neighborhood of $\Delta I/\Delta C = 0$ occurs classic [6] the self-oscillating process with a limit cycle in $4T$ and every $3T$ the unwanted transition through an extremum in the region of the capacitive nature of the electric power on value $\Delta C$. To stabilization $\cos \varphi \rightarrow$ in the region of the inductive nature of electric power self-oscillating steady-state of search must be carry out for a values $C$ less than its resonant value in a specific technological condition of the electric drive. This is done by setting the characteristic of the search $\Delta I/\Delta C = -\gamma$. At $-\gamma \rightarrow 0$ power factor $\cos \varphi \rightarrow 1$. Improving the quality of automatic search is achieved by modification of the conditions of the reverse impact of $C$ for steps search $\Delta C$ with different sign. [3, 4].

The stepping algorithm automatic search $\Delta I/\Delta C = -\gamma$ [7] based on the determination of the direction of change search coordinates $C_n$ in finite differences $\Delta C_n = C_n - C_{n-1}$, $\Delta I_n = I_n - I_{n-1}$ in the interval of durations $T = T_n - T_{n-1}$ ($n = 1, 2, \ldots, \infty$). The algorithm logic in the area $\Delta I/\Delta C = -\gamma$ is:

$$\begin{align*}
(\Delta C_n < 0, \Delta I_n \leq 0) & \rightarrow (\Delta C_{n+1} < 0) \\
(\Delta C_n < 0, \Delta I_n > 0) & \rightarrow (\Delta C_{n+1} > 0)
\end{align*}$$

(1)

works in conjunction with the algorithm

$$\begin{align*}
\text{Sign} (\Delta C_n \mid \Delta I_n) > 0 & \rightarrow (\Delta C_{n+1} < 0), \\
\text{Sign} (\Delta C_n \mid \Delta I_n) < 0 & \rightarrow (\Delta C_{n+1} > 0),
\end{align*}$$

(2)
\[ C_{n+1} = \sum_{n=1}^{\infty} \Delta C_n \text{ where } \alpha = \Delta C^2 \gamma, \]

ensuring the convergence of the search procedure to \( \Delta I/\Delta C = -\gamma \) with initial conditions on the right or left of the extremum.

Limit cycle of the oscillatory process in the area to the left of the minimum of \( I(C) \) has duration \( 2T \).

For the algorithm to work enough fact of existence of the extremum, regardless of its shape and lateral offsets \( I; C \). Additive error of sensor \( I \) does not affect the performance of the search algorithm, based on the determination of the differential signals \( \Delta I \). Possible use of the sensor \( I \) with a nonzero scale.

5. Modeling

Model figure 2 adaptive system is performed in terms of modelling dynamic systems Simulink (MATLAB) [8].

\[ \text{Figure 2. The model of adaptive system of automatic stabilization of the power factor } \cos \varphi \rightarrow 1 \text{ in the field of the inductive nature of the electric powers. The left part is a structural dynamic model of the electric drive. Settings “Slider Gain3” correspond to } 1/L \ (L = 50 \mu H) \ “Slider Gain4” \div R \ (R = 0.15 \Omega). \text{Configure a “Sine Wave” is } \omega = 11309 \ s^{-1}[3]. \text{“Product1” unit performs the operation of dividing the input variable for } C_n. \text{The right part is the control algorithm.} \]

Measurement of the total current \( I \) at the output of the model is managed SFC (“Sine Wave” together with “Product”) are used to detect high-frequency variable \( I(t) \) (“Abs1”, filter “Transfer Fcn5” with \( W(s) = 1.57/(0.01^2 s^2+0.2 s+1) \). The value of \( |I(t)| \) to be configured by a circuit of negative feedback, consisting of the same detector (with filter) \( U_C(t) \), of element comparisons \( U_{sup} = 380 \ V \) (“Constant2”) with amplitude \( |U_C(t)| \), “Integrator2” and “Sine Wave”. Unit “Product1” implements the operation \( 1/C_n \). The settling time of transients in the model of the actuator is \( t = 0.2 \ s \). Algorithm of automatic search is implemented in terms of Digital Simulink [8] with the period of quantization \( T = 0.2 \ s \). The magnitude \( \Delta C_n \) and \( \Delta I_0 \) are computed using elements of the delay \( W(z) = 1/z \), where “\( z \)” is the argument of the mathematical apparatus of analysis of digital automatic systems (“Z-transform” [8]). The control action \( C_n \) is formed by of the discrete integrator \( W(z) = Tz/(z-1) \) [7] with the configuration \( \Delta C_n = 4 \ \mu F \) (“Gain4” \div 2 \ 10^5) and the initial conditions “171 \ 10^{\pm 2} “(C \ = \ 171 \ \mu F). Block “Produkt3” and “Sign1” implement the logic of the algorithm (2).The operators “Sign2”, logic (“Switch1”) provide separate conditions of reverse \( C_n \) for \( \pm \Delta C_n \) according to algorithm (1)

While modeling accepted \( |\gamma| = 6 \ 10^5 \ [A/2] \) the corresponding \( \cos \varphi \approx 0.99 - 0.98 \). When \( \Delta C = 4 \ 10^6 \ F \) according to for \( \Delta C > 0 \) value \( \alpha = 9.6 \ 10^6 \ [F/A] \) (“Constant5”).

The purpose of the simulation is a proof of work algorithm (1) in the most adverse technological situation – a sharp decrease in the inductive – resistive load. This corresponds to the off part of the multi-engine electric drive when rebuilding or emergency in the cascade of centrifuges, especially significant in the case fits centrifuges high performance [9]. In such a situation, the possible transition of the energy system “HM – SFC” crossing the condition \( \cos \varphi = 1 \) in the region of the capacitive nature of power supply.
Figure 5 illustrates the operation of the adaptive system. Extreme characteristic curve 1 corresponds to the increased number of centrifuges in the cascade relative to the nominal condition (curve 2). The control system is enabled when the value $C = 171 \ \mu F$ that corresponds to the "overcompensation" in energy systems "HM – SFC".

**Figure 3.** Working of the adaptive algorithm of automatic search $\cos \varphi \rightarrow 1$ in the region of the inductive nature of the electrical power supply, to the left of the extrema curve 1...3.

The search algorithm finds the condition $\cos \varphi \rightarrow 1$ to the left of the minimum of $I(C)$ (resonance at $C = 165 \ \mu F$) when the oscillatory process in the range (158…162) $\mu F$ in the field of the inductive nature of the load. At time $t = 3 \ s$ switches off parts centrifuges and load SFC sharply decreased (Figure 3) (curve 3). When the capacitance value $C = 158...162 \ \mu F$ characteristic and the resonance characteristic in a state of "curve 3" the nature of power meets "overcompensation". Targeted search procedure finds the value of $\cos \varphi \rightarrow 1$ to the left of the new condition of the minimum of $I(C)$ in the range (130…134) $\mu F$ (the resonance at $C = 134 \ \mu F$). At time $t = 7 \ s$ restored the nominal number of centrifuges (curve 2). The search algorithm finds $\Delta I/\Delta C = \gamma$ to the left of the new extreme values $C = 145 \ \mu F$, providing $\cos \varphi \sim 0.98 – 0.99$ in the field of the inductive nature supply of the load. In all cases the duration of a limit cycle is $2T$. Change of the total current $I$ in the process of stabilization of a set of values $\cos \varphi$ (figure 3, the graphics “Scoup1”) are shares, units of amperes.

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**Conclusion**
1. The algorithm of the system of automatic stabilization $\cos \varphi \sim 0.99 \cdot 0.98$ in the field of the inductive nature of the power of multi-engine electric drive of centrifuges for uranium separation in a parallel capacitive compensation of reactive component of the total power is presented. Removed "overcompensation".
2. The work of the algorithm is based on the automatic search procedure in small neighborhood minimum full electric current, corresponding to the phenomenon of resonance at the frequency of the power supply.

3. For the adaptive operation of the system is only measuring total load current. The control algorithm is insensitive to additive errors of current sensor, does not require the measurement of active / reactive, apparent power, calculation of capacitance compensating capacitors, assessments of the nature of the supply (inductive / capacitive) of the power system, insensitive to additive errors of the sensor total current.

5. Limit cycle in a neighborhood of \( \cos \phi \rightarrow 1 \) in 2 times less in comparison with the classical procedure of automatic search of extremum.

6. The system can be realized based on of general technical devices of automatics. In a production environment, the algorithm can be activated periodically in depending on the specific technological situation or to be performed by the operator.

7. The system can be used for automatic stabilization of the \( \cos \phi \rightarrow 1 \) in general electrical networks with variable inductive – active load.

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