Adaptive system for automatic stabilization of the power factor for electric drives of separation device by means of serially connected capacitors bank

V D Borisevich and V M Juromskiy
National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe highway 31, Moscow, 115409, Russia
E-mail: VDBorisevich@mephi.ru

Abstract. A method for designing adaptive systems for automatic extremum search to stabilize the power factor of local electric power system of electric is considered. It consists in application of the serially connected capacitors compensating the reactive component of the total electric power of in parallel connected centrifugal machines usually called as an aggregate. Operation of the system just demands measuring voltage at the output of the static frequency converter for electric drives. The proposed control system is designed to stabilize the power factor close to unity in a case of alteration of parameters of a separation cascade or a single separation device in an aggregate. Such system can be operated continuously or connected occasionally depending on a technological situation. In addition, it totally excludes the phenomenon of overcompensation.

1. Introduction
As is known, the ability of the AC drive to produce the mechanical work is determined by the active power $P=UI\cos\varphi$, where $\varphi$ is the phase shift between the voltage $V$ and the current $I$ in the AC electric circuit. The reactive power $Q=US\sin\varphi$, creating the electromagnetic fields in the windings of the electric drive, does not perform the useful work, but loads additionally the power circuit, circulating in the circuit “generator – electric drive”. The total (apparent) power of the electric drive calculates as $S=\sqrt{P^2+Q^2}$ and measures by the current-voltage method. The energy efficiency of an electric drive is estimated as the ratio of the active power to the apparent one and calls as the power factor (PF) or $\cos\varphi=P/S$. Also known that the power factor for an electric drive has the maximum value at full mechanical load ($\cos\varphi=0.7–0.8$) and reduces idling to $\cos\varphi=0.2–0.3$. A fraction of the reactive power varies from about 50% $P$ to $(4–5)P$ and even more. According to the general-purpose industrial standard in many countries for PF equal to 0.95 the reactive component should be around 30% of the active power $P$. Thus, the designers of electric drives face with the following problems: 1 - current $I$ in electric circuits is determined in addition to the active component by the reactive one of the total power $S$, which increases the Ohmic losses in the power electric circuits; 2 - similarly, the reactive current additionally load the output circuits of a generator what results to necessity of increase in the power characteristics (dimensions, cost) of a generator or reduction of the active power amount which can be obtained from a generator. Therefore, designers are well aware of the law: more power, less PF that connected with loss of energy in distribution circuits, generators, and other equipment of...
power systems. All statements above are totally applied to a drive of the separation device for separation of isotopes (GCs). It is quite obvious that minimizing the consumption of electric power at the separation plants of GCs is the direct way to reduce the cost of electricity supplied by nuclear power plants [1].

2. Problem statement

The hysteresis synchronous motors (herewith after HM) with PF of (0.2–0.4), which are powered by the static frequency converter (SFC) forming the local power system “HM-SFC” with the non-standard frequency, are used as the drivers of the GCs [2]. Recently it has been demonstrated that increase of the PF in such power systems is possible either by traditional parallel inclusion of the compensating capacitors relatively to an unit of HMs in an aggregate of GCs, what provides the value of \( \cos \phi \approx 0.95–1.0 \) [2] or by connection in the series of such capacitors [3]. The features of the series compensation are based on the fundamental non-dependence of the resonance frequency

\[
o_0 = \frac{1}{\sqrt{LC}}
\]

of the serial power oscillating circuit \( L-R-C \) on the active resistance \( R \). In the case under investigation it means independence on all kinds of the active electrical resistances in the power system and reduction of the output voltage in a SFC providing the staffing voltage for a HM at the resonance frequency \( o_0 \) proportionally to the quality factor \( \eta = \omega L/R \). At a constant value of the capacitance \( C \) of the compensating capacitor corresponding to the standard requirement for \( \cos \phi \approx 0.90–0.95 \), the most unfavorable for the operation of the power system is the inductive load reduction due to the destruction of GCs or the planned reconfiguration of the separation cascade. In this case, the power system can pass through the state when \( \cos \phi = 1 \) and reach the undesirable mode known as “overcompensation” with a change in the nature of the power supply from the inductive to capacitive one. Restoring the given PF is based on changing the value of the compensating capacitors \( C \) manually or automatically according to the principle of the negative feedback. In the latter case, the displacements of the power system to the overcompensation mode leads to the changing a sign of the negative feedback in the automatic control circuit of the capacity \( C \), which leads to loss of its function.

In this paper the HM-FSC complex is considered as the power system stabilized in the state of the resonance at the frequency power of the adaptive automatic system. It is based on the automatic search of the minimum of the voltage \( U \) at the output cleats of a FSC as the function of modification of the compensating capacitance \( C \) which is connected in the series with a HM.

The extremum (minimum) of the \( U(C) \) function under the condition of the resonance corresponds to \( \cos \phi = 1 \). The use of this algorithm demonstrates that it totally eliminates the phenomenon of overcompensation. The problem is considered in the framework of the engineering approach. To be specific, we set that a HM has the frequency of the supply \( f = 1800 \text{Hz} \), the supply voltage \( U_s = 380 \text{V} \), and its other parameters are as follows: \( L = 50 \mu \text{H}, R = 0.15 \Omega \) (the quality factor \( \eta = 3.8; \cos \phi \approx 0.25 \)).

From the position of the resonance phenomenon in the local power circuit HM-FSC with the serial capacitor compensation of the reactive component of the apparent power and the constant value of \( U_s \), the dependence of \( U[V] \) at the exit of a FSC on the value of the compensating capacitor \( C \mu \text{F} \) takes the form of the extreme characteristic presented as the curve 2 in figure 1 for which \( dU/dC = 0 \) what corresponds to the equality \( \cos \phi = 1 \). Alteration of the drive parameters, when for some reason the number of HM is changed in an aggregate leads to modification of the \( U(C) \) dependence in the coordinate space \( \{ U; C \} \) shown in figure 1. It may move to the left or right sides simultaneously displacing the voltage extremum corresponding to the \( dU/dC = 0 \) condition (see the curves 1, 2, and 3 in figure 1).
The figure 2 in figure 1 corresponds to the initial number of HMs, as well as the curves 1 and 3 correspond to the decreased and increased by 10% number of HMs, respectively. After the resonance tuning the value of $C_0=157 \, \mu F$ for the initial number of HMs, the load increase leads to deterioration of the PF value (the curve 3) whereas the load decrease results to the undesirable phenomenon of "overcompensation" (the curve 1).

Because of the frequency resonance independence of the value of the active resistance $R$ of a HM at the constant voltage $U_s$ and the constant value of the $Q$-factor for the altering number of HMs, the minimum voltage $U$ at the output of a FSC does not displace in a vertical direction in the coordinate space $\{U; C\}$ unlike a similar situation in the case of the parallel resonance [2].

3. Object of the extremum control

The attribute of the maximum energy efficiency for the local energy system HM-FSC (at the condition of $U_s=$const) is adopted the minimum extreme dependence of the voltage $U(C)$ at the output cleats of a FSC the corresponding $dU/dC=0$ (min) which means for the specific process conditions of the resonance in the series $R-L-C$ power circuit the absence of the reactive component in the apparent power consumption and $\cos \phi=1$.

The control problem consists in identification and track the value of $dU/dC=0$ (min) of the extremum characteristics of $U(C)$ in the coordinate space $\{U; C\}$ when the simultaneous automatic stabilization of the $U_s$ voltage takes place. The supply voltage $U_s$ of an electric drive is stabilized by a control loop with the negative feedback, including the components as follows. These are the sensor for the $U_s$ value; the element comparing $U_s(t)$ with a given value of $U_{spec}=380 \, V$; an automatic controller with an integrator as of the control law; a FSC, an output signal $U$ from which changes by the output of a regulator; and a HM is represented by the $L-R$ parameters (see figure 2).

4. Algorithm for the automatic search of the extremum

The work of the step-by-step automatic algorithm to search the extremum is based on determining the direction of alteration in the search coordinates with $C(t)$ relatively to the operating point $\{U; C\}$ in the extreme dependence $U(C)$ in which $dU/dC=0$. In the finite differences it looks like $\frac{\Delta U_n}{\Delta C_n}=0$. Here $n=1, 2, \ldots, \infty; \Delta C_n=C_n-C_{n-1}$ is an amplitude of a search step (the capacitance value for one tuning compensating capacitor) in the range of duration $T$ for the $n$th search step. While $C_n, C_{n-1}$ are the values of a capacitor in the circuit $L-R-C$ in the moments of time $T_n, T_{n-1}$, and $\Delta U_n=U_n-U_{n-1}$ is the increment of the $U$ voltage at the output cleats of a FSC in the logic as follows:

$$(\text{Sign } [\Delta C_n \Delta U_n ] <0) \rightarrow (\Delta C_{n+1} >0)$$
$$(\text{Sign } [\Delta C_n \Delta U_n ] >0) \rightarrow (\Delta C_{n+1} <0)$$
and $ΔC_{n+1} = \sum_{n=1}^{∞} ΔC_n$.

The algorithm is characterized by the self-oscillating process relatively to the value $ΔU/ΔC = 0$.

**Figure 2.** The system of the automatic optimization of the PF in the HM-FSC complex with the regulatory impact by a change of the capacitance with respect to the value of the nominal $C_0$ capacitance.

The notations used in figure 2 are as follows: $L$ is the inductance; $R$ is the active resistance of the HM windings; $C_0$ is the principal capacitor of the serial resonant contour $L-R-(C_0 + ΔC_n)$; $ΔC_n$ are the switchable tuning capacitors. The searching impact $\sum_{n=0}^{∞} ±ΔC_n$ is generated by the solid relays, switching the tuning capacitors $ΔC_n$. Since the work of the step-by-step searching algorithm is based on the assessment of the partial derivatives of the static extreme characteristic, the duration $T$ of the searching “step” must be greater than the settling time for the transient processes in the system of stabilization of $U_s$.

**5. System model and its tuning**

In this case the control object is the resonant system corresponding to the curve 2 in figure 1, in which the minimum value of $U(C)$ corresponds to the ratio $U_s/Q = 380/3.8 = 100$ V.

The control algorithm is implemented as a digital-based discrete functional blocks at the Simulink Toolbox of MATLAB [4]. The sampling time for modeling is adopted as the duration of the searching step $T$ of the search algorithm. The model $U(C) = αC^2 + C_0$ that corresponds to the curve 2 in figure 1, is based on the multiplication block “Produkt 1”, in which the parameter “Gain 1” is customized as $α= 0.034 \text{ V/μF}$ and $C_0 = 157 \text{ μF (“Constant 4”).}$

The deviations $U(C)$ the extreme values of which are shown in figure 1 are carried out in the element “Sine Wave”, by displacement of the $C$ coordinates according to the harmonic low. The change in the number of HMs is carried out in the block “Step 1”. The first difference at the entrance $ΔC_n$ and the exit $ΔU_n$ of the characteristics $U(C)$ are calculated using the time delay $T$ (in one “step”) with $W(z) = 1/z$, where $z$ is the argument of the discrete Z-transform analysis of the digital control systems [4]. The terms of reverse $[ΔC_n ΔU_n] = 0$ are implemented the block “Product 2”, and by the operator “Sign”. The search impact is formed by the discrete integrator $W(z) = T/(z-1)$. The increment output of the integrator $ΔC_n$ per unit “step” is configured by the transmission factor of the amplifier “Gain 4”. The indicators “Scope” and “XY Graf” are intended for monitoring of the system parameters.
During the simulation it is taken conditionally that $T = 1$. In practice, the value of $T$ should be longer than the time of the forced discharge of the special industrial capacitors for compensation of the reactive power (in dozens of seconds) and more than the regulation time in the system of automatic stabilization $U_s$ (in seconds). The amplitude of the search step $\Delta C_n$ is selected from the conditions of the confident distinction increment of the $\Delta U_n$ voltage from the exit of a SFC and following to the results of simulation is approximately $(1-3) \mu F$.

**6. Results of simulation and discussion**

Figure 4 illustrates the situation when a part of GCs in an aggregate is fallen out what results to sharp displacement of the characteristic $U(C)$. In the model it means the transition from the curve 2 to the curve 1 in figure 1 with appearance of the “overcompensation” phenomenon or the jump from the curve 1 to the curve 2 in the same figure. As can be seen, the search algorithm takes out the power system in a new state of resonance with $\cos \phi = 1$ after a few “steps” $\Delta C_n = 3 \mu F$.

**Figure 4.** Working off the resonance in the power circuit in the case of a failure with GCs. $\Delta C = 3 \mu F$. 

**Figure 3.** The system model in the terms of the Simulink Toolbox of MATLAB.
After tuning of the system by means of the searching algorithm the resonance of the energy system at $C=157\mu F$ (the curve 2 in figure 4) at the time moment $t=200s$ the total number of GCs in a separation cascade was changed (the curve 1 in figure 4) and at the time $t=250s$ the number of GCs was restored (the curve 2 in the same figure 1). Figure 5 demonstrates the auto-search of the mode $\cos\phi=1$ when takes place the slow shift of $U(C)$ following to the harmonic low with the frequency $0.001\ Hz$ between the curves 1 and 3 in figure 1 corresponding to the drift of the electric parameters of the HMs in time. The centers of the self-oscillation mode on the search coordinate $C_n$, where $\Delta U_n/\Delta C_n=0$ (upper part of the figure 4) corresponds to moving over the coordinate $C$ with the extrema caused by the drift of $U(C)$. The lower part of figure 5 illustrates a change of the search coordinate $C_n$ in tracking the resonance of the “drifting” $U(C)$.

**Figure 5.** Automatic search of $\cos\phi=1$ with a slow drift of $U(C)$.

In the process of fixing the steady-state regime of search, the deviation on both sides of the minimum $U(C)$ (“Scope 10”) does not exceed one Volt, and the errors of deviation from the specified value $PF=1$ of an energy system are insignificant. Note that the regime of “overcompensation” in the power system is also absent. The results of simulation showed in figures 4 and 5, allow us to make a conclusion on the possibility of realization of the working mode for the energy system with $\cos\phi=1$.

7. **The practical implementation of the system**

The control algorithm is implemented with the standard functional resources of the general industrial automatic controllers with freely programmable structure. The electrical industry produces a wide range of the specialized capacitors for the reactive power compensation in the power circuits and the high-current thyristors for their switching. In the mode of resonance and the stable supplying voltage $U_s=380V$ for a GC, the voltage $U$ at the cleats of a FSC is reduced in proportion to the $Q$-factor of the power oscillating contour and is equal approximately to $100V$, what reduces the performance requirements for a FSC.

In case of the industrial conditions the control system of the power factor can be operated continuously or switched periodically as well as be fulfilled interactively by an operator depending on the technological situation.
8. Alternative applications
The developed system can be applied to stabilize $\cos \varphi = 1$ not only in the case under investigation, but in numerous industrial technological systems and objects with variable inductive/resistive loads. As the illustrative examples one may review the induction melting furnaces, the electrolysis process, the high-power electric motors for various applications, i.e. practically at any industrial enterprise or in stand-alone (on-board) power systems with limited resources, including the case when the power or on-board voltage in a circuit is less than in the staffing or in unstable conditions.

Conclusions
1. It is presented the engineering approach to design the adaptive system for automatic stabilization of the PF for the electric drives of GC based on an automatic search for the minimum of the output voltage $U$ at the cleats of a FSC on the value of the compensating capacitance $C$ connected in series with the electric drive.
2. The control system is realized by the conventional industrial engineering means of controls. In the working mode it just requires the regular voltage sensors to control the output voltage for a FSC and a HM.
3. The output voltage for a in the $Q$-factor times smaller than that for a HM in the optimum regime.
4. The instability in the supply of voltage at the cleats of a FSC, when the parameters of GCs or HM are changed, do not effect to the nominal value of the supply voltage of a HM and the energy efficiency of the power system “HM-SFC”.
5. In this working mode of the adaptive system the mode of “overcompensation” is totally excluded.

References
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