SYNERGETIC SYNTHESIS OF NONLINEAR INTERCONNECTED CONTROL FOR TURBOGENERATORS

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Abstract

The analytical synthesis problem of coordinating regulator for power system, consisting of two turbogenerators, working at big power network, is considered in this article. We used nonlinear, non-conservative and interconnected model of such power system. There are four control channels in this case. To solve this hard task we used main approach of synergetic control theory. This approach was developed by professor A.A. Kolesnikov. Briefly synthesis procedure is described. The synthesized regulator provides stabilization of the generators excitation currents (synchronous EMFs), coordinated turbines rotation frequency, asymptotic stability of the closed-loop system in the whole and compensates the external low-frequency harmonic disturbances that act to generators. Example of synthesis is considered.

KEYWORDS: synergetic, control, power system, turbogenerator, attracting manifolds.

1 Introduction

The modern electric generators and turbines (turbogenerators) on its electromechanical features are known in the whole world as the best power sources for different power systems (PS). Turbogenerators and power stations as a whole are supplied automatic control systems that must provide high reliability of work. However these systems have variety of hidden and in principal incurable drawbacks. The main reason for it is immaturity of the that linear ideology of the classical control theory, which was laid in the foundation of the control systems design for such essentially nonlinear and multiply connected objects as turbogenerators.

An extremely important quality of turbogenerators is there nonlinearity. The other distinctive feature causing lacks of the modern control systems is nonlinear dynamic link between a turbine and a synchronous generator (SG) both in a single turbogenerator and in a group of turbogenerators of a power station. At the present time excitation regulators [1] and frequency regulators of the turbogenerators are synthesized as separate independent devices. However it is obvious that excitation and frequency control channels undoubtedly influence each other since SG and the turbine are interconnected objects. This interconnectivity is especially magnified in peak and fault situations when these objects are working in the large deviations regime and hence revealing there nonlinear qualities to a large degree. The other feature of the modern turbogenerators is their work in conditions of action peak (worst) of disturbances on the PS's part. Such disturbances promote the appearance of system fluctuations that can bring about breach of PS's stability, asynchronous move and in general appearance of system damage.

Professor A.A. Venikov said [2]: " ... turbine emergence control is effective when it's tightly connected with SG excitation control. Therefore it is necessary to realize a simultaneous coordinated control by generator's excitation and mechanical capacity of turbine from one complex regulator". The turbogenerator's peculiarities listed here indicate that at the present time there is urgent necessity in solution of the new problem of synthesis and design of nonlinear coordinating regulators that have the channels of interconnected cohered control of excitation voltage and rotation frequency for a turbogenerator or for these groups. Such tasks can't be solved by the existing control systems for the separate turbogenerators.

2 Statement of control task

There is power system, consisting of several turbogenerators that work at common big power network. The vector, nonlinear, interconnected control task for it is formulated as follows: it is necessary to synthesize nonlinear interconnected regulator with the excitation control channels U_{1i} and the frequency control channels U_{2i} for each turbogenerator respectively. The functions of this regulator are

1. stabilization of the generators excitation currents (it's equivalent stabilization of the generators EMFs) and turbines rotation frequencies, it should provide coordinated turbines rotation frequency;
2. guaranty of asymptotic stability of the closed-loop system in the whole;
3. providing of the desired damping qualities in the small deviations regime;
4. compensation of the external low-frequency harmonic disturbance.

There is problem of base approaches choice for synthesis of vector, nonlinear, interconnected regulator that ensures listed functions. We suggest to use main approach of synergetic control theory for solving this hard task. This approach was developed by professor A.A. Kolesnikov [3-6] and it's named method of analytical designing of aggregated regulators (ADAR). It provided effective solution of the vector control task formulated above. ADAR method allows to synthesize control laws for nonlinear high order objects with several control channels. It ensures cohering of the physical qualities of the turbogenerator and the technological requirements to the dynamic and static qualities of the power system in the regime of small and large deviations from the desired state. Synergetic control laws also assure increased robustness of synthesized systems to changes the object and regulator parameters.

There is fact that speaks in favour of vector control for turbogenerators as follows independent turbogenerator control by SG's excitement channel brings to appear degenerative mode with special control. Using interconnected, two channels turbogenerator's regulator with channel of turbine rotation frequency and channel of SG's excitement avoids degenerative modes of motion. It's needed to note that exactly use the ADAR method allowed to provide asymptotic stability of power system in the whole. We successfully solve this control task as for a turbogenerator, so for the turbogenerators group consisting of two and three turbogenerators.

3 Model of control object

As model of control object we use the turbogenerator's model [1, 2] that generally accepted for control by transient modes of power systems. The equations of electric part are recorded in ***dq0*** axises. Let's make assumptions that SG is a machine with a variable number of poles, it is not saturated; has symmetrical stator windings ($u_0 = 0,\ i_0 = 0$); has sine form of magnetic field distribution in the air gap, and hysteresis influence is neglected. We'll neglect the electromagnetic transients in the stator and damping circuits [1].

In real power systems turbogenerators often are subjected to external harmonic disturbance $F(t)$, so there is problem of control laws synthesis that compensate such disturbance. According ADAR method [3-6] to solve this problem, it's necessary to increase phase space nondisturbed object by differential equations that describe this disturbance, for example, harmonic disturbance

$$\begin{aligned} &\frac{dw_1}{dt} = w_2; \\ &\frac{dw_2}{dt} = -\Omega^2 w_1; \\ &F(t) = w_1. \end{aligned} \tag{3.1}$$

We'll suppose that state variables of model (3.1) are measured.

Thus, the model of power system, consisting of two turbogenerator with taken admissions and equations (3.1), has the form of:

$$\begin{aligned} &\frac{dx_1}{dt} = x_3; \quad \frac{dx_2}{dt} = x_4; \\ &\frac{dx_3}{dt} = b_1(x_7 - a_1 x_5^2 - a_2 x_5 x_6 \sin(x_1 - x_2 - \alpha_{12}) + c_1 x_9); \\ &\frac{dx_4}{dt} = b_4(x_8 - a_3 x_6^2 + a_2 x_5 x_6 \sin(x_1 - x_2 + \alpha_{12}) + c_1 x_9); \\ &\frac{dx_5}{dt} = b_2(-x_5 - a_4(x_3 - x_4)\sin(x_1 - x_2 - \alpha_{12}) + U_{11}); \\ &\frac{dx_6}{dt} = b_5(-x_6 - a_5(x_3 - x_4)\sin(x_1 - x_2 + \alpha_{12}) + U_{12}); \end{aligned} \tag{3.2}$$

$$\frac{dx_7}{dt} = b_3(-x_7 - a_6 x_3 + U_{21});$$
$$\frac{dx_8}{dt} = b_6(-x_8 - a_7 x_4 + U_{22});$$
$$\frac{dx_9}{dt} = x_{10};$$
$$\frac{dx_{10}}{dt} = -\Omega^2 x_9;$$

where x_1, x_2 – angles between SG's EMF and synchronous axis $\boldsymbol{q}$ (rotation angle of the SG with respect to the rotation axis of the constant voltage bus), x_3, x_4 – SG's slips, x_5, x_6 – synchronous generators EMFs on the $\boldsymbol{q}$ axis, x_7, x_8 – mechanical powers of turbines, x_9, x_{10} – state variables of disturbance model, U_{11}, U_{12} – excitation control channels, U_{21}, U_{22} – turbines control channels, ω_0 – network frequency, α_{12} – additional angle of mutual generator conductivity, a_i, b_j, $i = 1, \ldots, 7$, $j = 1, \ldots, 6$ – object constants, Ω – frequencies of disturbances, c_1 – constant coefficient.

Thus, the system of equations (3.2) is the nonlinear, non-conservative and interconnected model of power system, containing two turbogenerators. In this case there are four control channels ($m = 4$).

4 Control strategies synthesis

We'll use ADAR method for control laws synthesis [3-6]. We require minimum of the following optimizing functional to be satisfied:

$$J = \int_0^\infty \left(\sum_{s=1}^{m} [T_s^2 \dot{\psi}_s^2(t) + \psi_s^2] \right) dt. \tag{4.3}$$

Asymptotic stability of the motion must be ensure at some area of the phase space or in the large. The equations of the extremals ensuring minimum of the functional (4.3) have the following form:

$$T_s \dot{\psi}_s(t) + \psi_s = 0, \quad s = 1, \ldots, m, \tag{4.4}$$

where ψ_s, $\dot{\psi}_s$ – attracting invariant manifold and it full derivative accordingly, T_s – time constant.

Attracting manifolds ψ_s are functions of control object state variables. They show desired characteristics (invariants) of the closed-loop system. Equations (4.4) are named base functional equations of ADAR method and their asymptotic stability condition with respect to the manifolds ψ_s has the elementary form of $T_s > 0$. Since the solution of system (4.4) is stable, motion after the transients must the following relations

$$\psi_s(x_1, \ldots, x_n) = 0, \quad s = 1, \ldots, m. \tag{4.5}$$

The representing point can't be present at all the manifolds at the same time so it first approaches the intersection of the manifolds (4.5). Then it moves to the end state along the manifolds intersection.

Let's consider synergetic synthesis of control vector $\mathbf{U}(U_{11}, U_{12}, U_{21}, U_{22})$ that moves the object from arbitrary initial state located at some allowed area to the desired point of the phase space. Synthesized controls must satisfy optimization conditions that recorded in the form of differential equations system (4.4). So the first stage of synthesis procedure is writing the system (4.4) in extended form, that is with provision for object (3.2):

$$T_s \sum_{j=1}^{n} \frac{\partial \psi_s}{\partial x_j} \frac{dx_j}{dt} + \psi_s = 0, \quad s = 1, \ldots, m, \tag{4.6}$$

where $n = 1, \ldots, 10$ – dimension of object (3.2).

Last equations allow to synthesize different control laws, it depends from concrete forms of manifolds ψ_s. Solving algebraic equations system (4.6) jointly we get the control laws for the object.

5 Example of synthesis

Let's set the following group of attracting manifolds

$$\begin{aligned}
\psi_1 &= \beta_{11}(x_5 - x_5^0) + \beta_{12}(x_6 - x_6^0);\\
\psi_2 &= \beta_{21}(x_5 - x_5^0) + \beta_{22}(x_6 - x_6^0);\\
\psi_3 &= \beta_{31}(x_7 + \varphi_1 + c_1 x_9) + \beta_{32}(x_8 + \varphi_2 + c_1 x_9);\\
\psi_4 &= \beta_{41}(x_7 + \varphi_1 + c_1 x_9) + \beta_{42}(x_8 + \varphi_2 + c_1 x_9),
\end{aligned} \tag{5.7}$$

where x_5^0, x_6^0 – desired values of generators EMFs.

Form of manifolds (5.7) is bound up with necessity to realize following technological invariants: stabilization of SG's EMFs $x_5 = x_5^0, x_6 = x_6^0$ and stabilization of SG's angles $x_1 = x_1^0, x_2 = x_2^0$.

The manifolds (5.7) should satisfy (4.4). Then according (4.5) we have decomposing system on $\psi_1 = \psi_2 = 0$, $\psi_3 = \psi_4 = 0$:

$$\begin{aligned}
&\frac{dx_1}{dt} = x_3; \quad \frac{dx_2}{dt} = x_4;\\
&\frac{dx_3}{dt} = b_1(-\varphi_1 - a_1(x_5^0)^2 - a_2 x_5^0 x_6^0 \sin(x_1 - x_2 - \alpha_{12}));\\
&\frac{dx_4}{dt} = b_4(-\varphi_2 - a_3(x_6^0)^2 + a_2 x_5^0 x_6^0 \sin(x_1 - x_2 + \alpha_{12}));
\end{aligned} \tag{5.8}$$

To determine the functions φ_1, φ_2 we introduce the additional attracting manifolds

$$\begin{aligned}
\psi_5 &= x_3 + \gamma_1(x_1 - x_1^0);\\
\psi_6 &= x_4 + \gamma_2(x_2 - x_2^0)
\end{aligned} \tag{5.9}$$

where γ_1, γ_2 – constant coefficients, x_1^0, x_2^0 – desired values of generators angels.

Implementation of $x_1 = x_1^0, x_2 = x_2^0$ allows to guarantee asymptotic stability of the closed-loop system in the whole. Also it allows to stabilize turbines rotation frequency.

Then solution of the equations

$$T_k \dot{\psi}_k(t) + \psi_k = 0, \quad k = 5, 6,$$

yields

$$\begin{aligned}
\varphi_1 &= -a_1(x_5^0)^2 - a_2 x_5^0 x_6^0 \sin(x_1 - x_2 - \alpha_{12}) + \frac{1}{T_5 b_1}\Big(x_3(T_5\gamma_1 + 1) + \gamma_1(x_1 - x_1^0)\Big); \\
\varphi_2 &= -a_3(x_6^0)^2 + a_2 x_5^0 x_6^0 \sin(x_1 - x_2 + \alpha_{12}) + \frac{1}{T_6 b_4}\Big(x_4(T_6\gamma_2 + 1) + \gamma_2(x_2 - x_2^0)\Big).
\end{aligned} \tag{5.10}$$

Having written (4.4) with provision of (5.7), (5.10) and (3.2), we'll get algebraic equations system. Solving this system jointly with respect we'll find sought control laws for the object (3.2):

$$\begin{aligned}
U_{11} &= -p_1x_3 - p_2x_7 + x_5 - p_3(x_5 - x_5^0) - p_4x_9 - p_5(x_1 - x_1^0) + p_6 + \\
&\quad + (a_6(x_3 - x_4) + p_7)\sin(x_1 - x_2 - \alpha_{12}); \\
U_{12} &= k_1x_4 + k_2x_8 + x_6 + k_3(x_6 - x_6^0) + k_4x_9 + k_5(x_2 - x_2^0) + k_6 + \\
&\quad + (a_7(x_3 - x_4) + k_7)\sin(x_1 - x_2 + \alpha_{12}); \\
U_{21} &= p_8(x_3 - x_4)\cos(x_1 - x_2 - \alpha_{12}) - p_9x_3 + p_{10}x_7 + p_{11}x_5^2 + p_{12}(x_5 - x_5^0) + \\
&\quad + (p_{13}x_5x_6 + p_{14})\sin(x_1 - x_2 - \alpha_{12}) - p_{15}(x_1 - x_1^0) - p_{16}x_9 - p_{17}x_{10} + p_{18}; \\
U_{22} &= -k_8(x_3 - x_4)\cos(x_1 - x_2 + \alpha_{12}) - k_9x_4 - k_{10}x_8 + k_{11}x_6^2 - k_{12}(x_6 - x_6^0) + \\
&\quad + (k_{13}x_5x_6 - k_{14})\sin(x_1 - x_2 + \alpha_{12}) - k_{15}(x_2 - x_2^0) - k_{16}x_9 - k_{17}x_{10} + k_{18},
\end{aligned} \tag{5.11}$$

where $p_i, k_i,\ i = 1, \ldots, 18$ – constant coefficients, depending on object coefficients and the regulator parameters.

Analytically this laws can be received by means computer algebra programs.

Asymptotic stability conditions for the system (3.2) with synthesized control laws (5.11), ensuring that the system gets to the intersection of the manifolds (5.7) and then moves to the stabilized state, have form:

$$\begin{gathered}
\gamma_1 > 0, \gamma_2 > 0, T_i > 0, \quad i = 1, \ldots, 6, \\
\beta_{11}\beta_{22} \neq \beta_{12}\beta_{21}, \quad \beta_{31}\beta_{42} \neq \beta_{32}\beta_{41}.
\end{gathered}$$

The simulation results for this example are presented in Fig. 1–6. The following object coefficients are chosen: $a_1 = 0.263,\ a_2 = 0.03, a_3 = 0.405, a_4 = 0.09,\ a_5 = 0.081,\ a_6 = 20,\ a_7 = 25, b_1 = 1/7, b_2 = 0.15,\ b_3 = 0.286,\ b_4 = 1/8,\ b_5 = 0.119,\ b_6 = 0.25,\ \alpha_{12} = -0.95, \Omega = 0.02,\ c_1 = 1$; the regulator parameters: $x_5^0 = 1.5,\ x_6^0 = 1.3,\ x_1^0 = \pi/3, x_2^0 = \pi/6, T_1 = T_3 = 5,\ T_2 = T_4 = 4,\ T_5 = T_6 = 2,\ \gamma_1 = \gamma_2 = 1, \beta_{11} = \beta_{31} = 2, \beta_{12} = \beta_{21} = \beta_{22} = \beta_{32} = \beta_{41} = \beta_{42} = 1$.

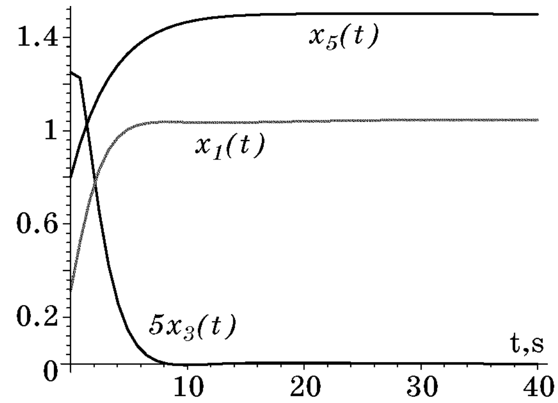

Figure 1: State variables x_1, x_3, x_5 transients

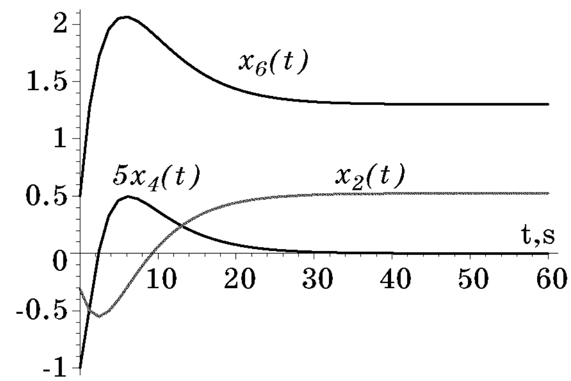

Figure 2: State variables x_2, x_4, x_6 transients

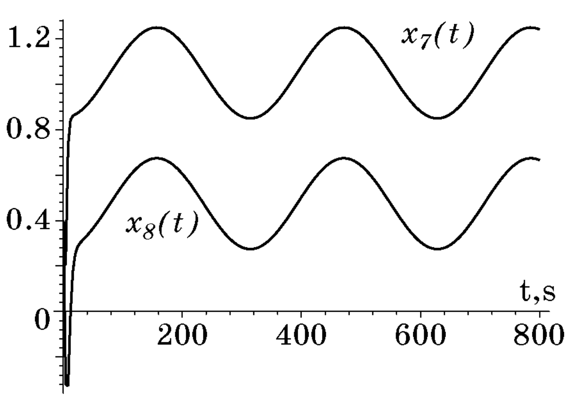

Figure 3: State variables x_7, x_8 transients

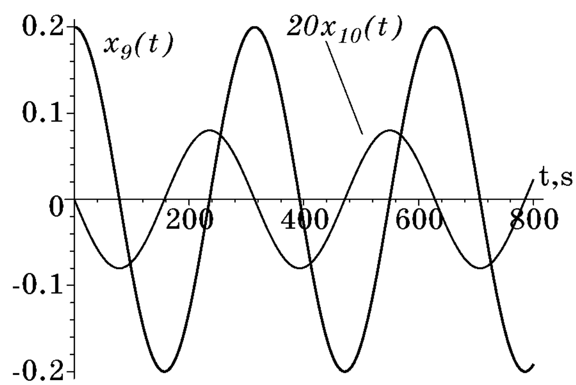

Figure 4: State variables x_9, x_{10} transients

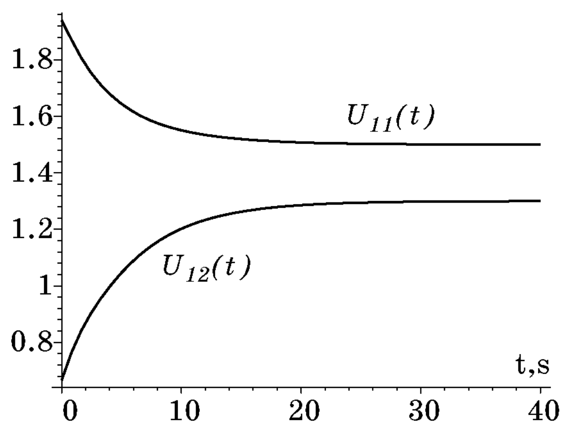

Figure 5: Controls U_{11}, U_{12} transients

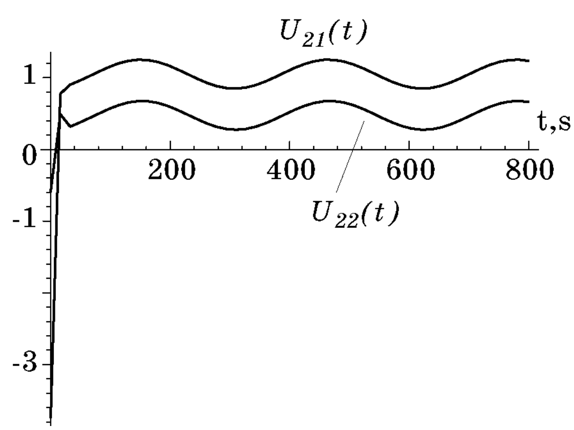

Figure 6: Controls U_{21}, U_{22} transients

6 Conclusion

Analyzing the modeling results we can make a conclusion that the synthesized control laws (5.11) ensure execution all supplied above control aims. So we solve the complex control laws syntheses task for the power system consisting of two turbogenerators, working at big power network.

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