Evaluation of the accounting the AVR of the generator in the power system model in the study of the subsynchronous resonance

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Abstract. The article discusses the model of the power system taking into account the automatic voltage regulator of the generator at the occurrence of a self-clearing fault on the line. In this case, the grid contains series compensation. The generator is an electromechanical system consisting of a turbine and a synchronous generator with an excitation system. Time plots of rotation angles deviations of rotating parts of turbine, twisting torques, and also plots of maximum deviations of rotation angles and twisting torques from the level of series compensation are shown with the indication of the area in which they grow in time.

1. Introduction

The case of the subsynchronous resonance occurrence in the turbogenerators and the methods of controlling it has been given several decades [1]. The first documented accidents due to subsynchronous resonance relate to 1970. Failures occurred at Mohave Power Station, USA. The main reason for the occurrence of low-frequency oscillations in high-power turbosets is the presence of devices with series capacitive compensation. At different times, theoretical and practical studies have been made of this phenomenon [2] and methods of its suppression [3, 4]. At the same time a relatively recent outages occurred in 2013 in a gas-turbine power plant providing an oil production facility in the northern Russia [5]. Thus, the measures taken to suppress torsional vibrations are not so effective as to avoid shutdowns.

One of the possible ways to prevent the development of torsional vibrations is to adjust the automatic voltage regulator (AVR) [6]. During simulation of the system with subsynchronous resonance without taking into account AVR, oscillations in the system were expected to increase. In this case, such effect occurred only within a certain range of the level of series compensation.

2. Problem description

The base system includes a two-mass turbine, a synchronous generator, a synchronous generator, power lines, load, series compensation (figure 1). The disturbance is a self-clearing fault on the line. The simulated circuit is obtained by modifying the circuit in the Matlab assembled for the case [7]. According to the results of research system without AVR, it was found that the amplitudes of the turbine masses oscillations has a maximum at the level of series compensation $\mu = 0.47$ and a three-phase ground fault as a perturbation. In the range $\mu = 0.39 \ldots 0.53$ oscillations are undamped, indicating the presence of positive feedback generated by the series compensation capacity.

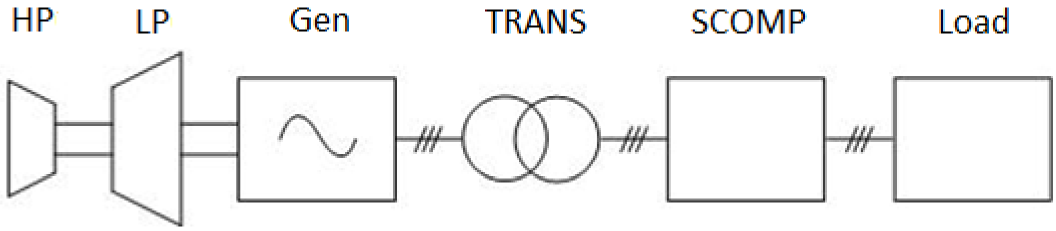

Figure 1. Power system model structure.

where HP – high pressure turbine section
LP – low pressure turbine section
Gen – generator
TRANS – transformer
SCOMP – series compensator
Load – electric load

3. Theory

The mathematical model describing the generator is represented by the Park-Gorev equations, the turbine is represented by the equations of mechanics, load and series compensation are represented by equations according to Kirchhoff 's laws.

Equations describing the power system with the two-mass model of the turbogenerator are represented in [8] and corrected as follows

$$\begin{aligned}&-(X_l+X_d)\frac{di_d}{dt}+X_{md}\frac{di_f}{dt}+X_{md}\frac{di_D}{dt}=\\&=\omega_b\left[(R_l+R_a)i_d-(X_l+\omega_r X_q)i_q+\omega_r X_{rnq}i_Q+e_{cd}+\upsilon_0\sin\delta_r\right],\end{aligned} \tag{1}$$

$$\begin{aligned}&-(X_l+X_q)\frac{di_q}{dt}+X_{mq}\frac{di_Q}{dt}=\\&=\omega_b\left[(X_l+\omega_r X_d)i_d+(R_l+R_a)i_q-\omega_r X_{rnq}i_f+\omega_r X_{md}i_D+e_{cq}+\upsilon_0\cos\delta_r\right],\end{aligned} \tag{2}$$

$$-X_{md}\frac{di_d}{dt}+X_f\frac{di_f}{dt}+X_{md}\frac{di_D}{dt}=\omega_b\left[-R_f i_f+\frac{R_f E_{fd}}{X_{md}}\right], \tag{3}$$

$$-X_{mq}\frac{di_q}{dt}+X_Q\frac{di_Q}{dt}=-\omega_b R_Q i_Q, \tag{4}$$

$$-X_{md}\frac{di_d}{dt}+X_{md}\frac{di_f}{dt}+X_D\frac{di_D}{dt}=-\omega_b R_D i_D, \tag{5}$$

where $\upsilon_f = R_f E_{ed}/X_{md}$.

Voltage drop across X_c is defined as

$$\frac{de_{cd}}{dt}=\omega_b(X_c i_d+e_{cq}), \tag{6}$$

$$\frac{de_{cq}}{dt}=\omega_b(X_c i_q-e_{cd}). \tag{7}$$

High-pressure section is given as

$$\frac{d\omega_1}{dt}=\frac{1}{M_1}\left[-D_1(\omega_1-1)-K_{12}(\theta_1-\theta_2)\right], \tag{8}$$

$$\frac{d\theta_1}{dt}=\omega_b(\omega_1-1). \tag{9}$$

Low-pressure section is described as

$$\frac{d\omega_2}{dt}=\frac{1}{M_2}\left[-D_2(\omega_2-1)+K_{12}(\theta_1-\theta_2)-K_{23}(\theta_2-\delta_r)\right], \tag{10}$$

$$\frac{d\theta_2}{dt}=\omega_b(\omega_2-1). \tag{11}$$

Generator equations are

$$\frac{d\omega_r}{dt}=\frac{1}{M_3}\left[T_m-T_e+K_{23}(\theta_2-\delta_r)-D_r(\omega_r-1)\right], \tag{12}$$

$$\frac{d\delta_r}{dt}=\omega_b(\omega_r-1), \tag{13}$$

where $T_e=i_q\psi_d - i_d\psi_q=(X_q-X_d)i_d\, i_q+X_{md}\, i_f\, i_q-X_{mq}\, i_Q\, i_d+X_{md}\, i_D\, i_q$.

Equations (1) - (13) form a system of 13 first order nonlinear ODE describing the operation of the grid, with the following variables: i_d, i_q, i_f, i_Q, i_D, e_{cd}, e_{cq}, ω_1, θ_1, ω_2, θ_2, ω_r, δ_r, where i_d, i_q, i_f, i_Q, i_D – direct and quadrature stator currents, excitation current, damper windings currents, e_{cd}, e_{cq} – direct and quadrature voltage drop across capacitance, ω_1, ω_2, ω_r – generator section angular velocity, θ_1, θ_2, δ_r, – angle of turbine section, X_{md}, X_{mq} – direct and quadrature mutual induction inductive reactance, X_d, X_q – direct and quadrature stator inductive reactance, X_f – excitation winding inductive reactance, R_D, R_Q, X_D, X_Q – direct and quadrature damper windings active resistance and inductive reactance, R_a, R_f – stator and excitation windings active resistances, X_l, R_l – power transmission line inductive reactance and active resistance, D_1, D_2, D_r – turbine section damper coefficients, M_1, M_2, M_3 – turbine section inertia constants, K_{12}, K_{23} – turbine section stiffnesses, T_m, T_e – mechanical and electromagnetic torque.

4. Simulation results

The scheme and simulation results of the case neglecting AVR are shown in figures 2, 3.

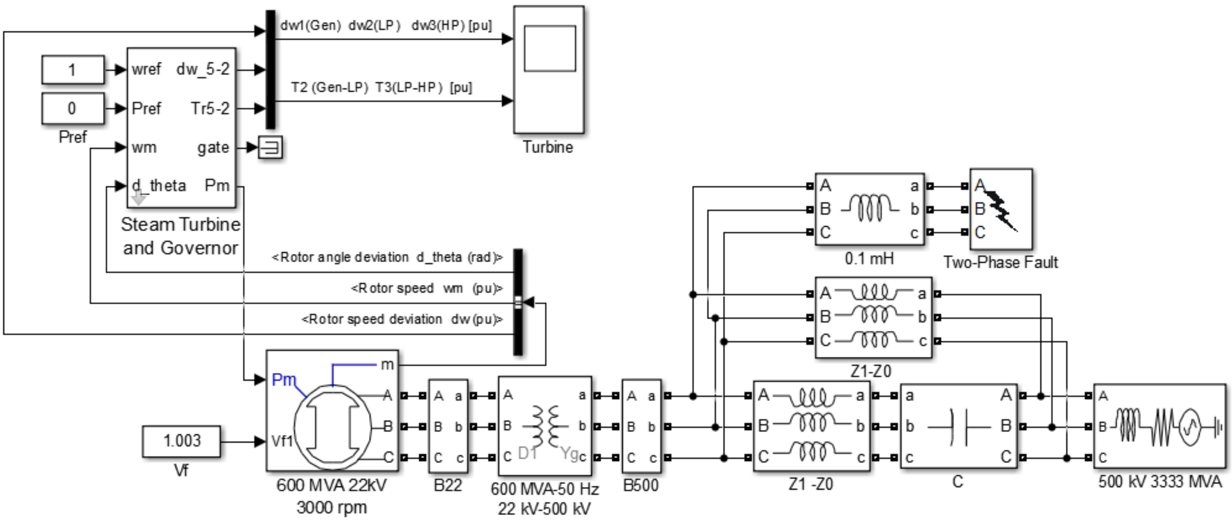

Figure 2. Neglecting AVR Matlab model.

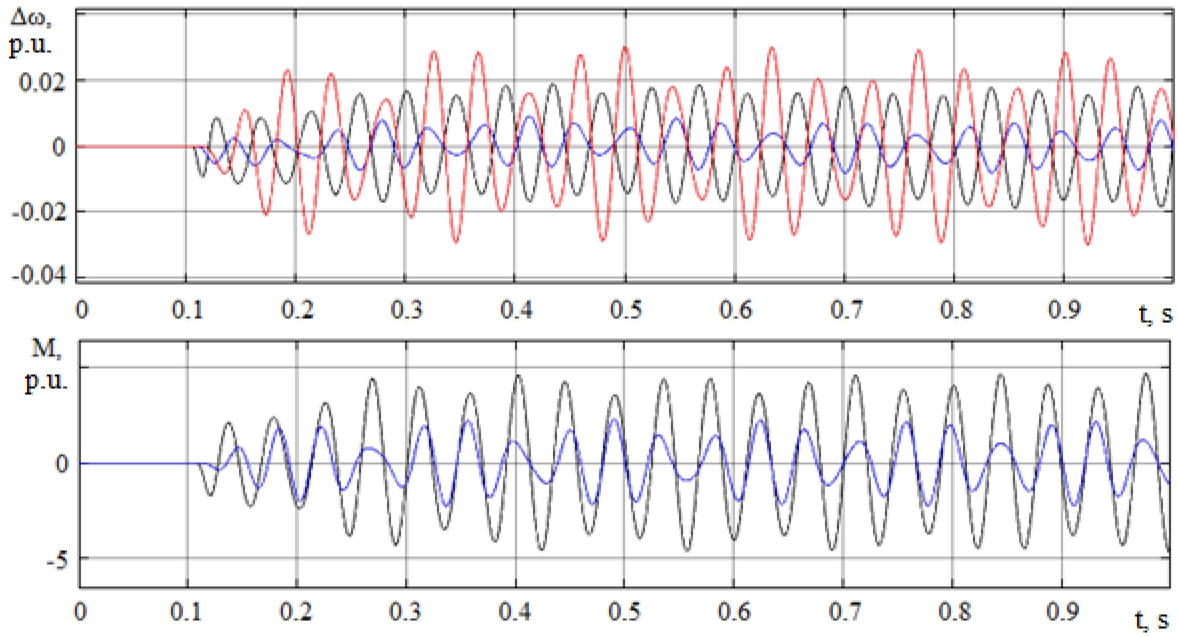

Figure 3. Time diagrams of the angular velocities deviations and torsional moments for the case without AVR at the level of series compensation μ = 0.5.

The model with AVR is presented in figure 4, the AVR of an alternative structure [9] is shown in figure 5. Time diagrams of angular velocity and torsional moments (figure 6) are not qualitatively different from the previously obtained (figure 3). Then, the plots for the series compensation level μ = 0.35 … 0.7 were obtained and the dependences of the mechanical coordinates amplitudes from this parameter were plotted (figures. 7, 8).

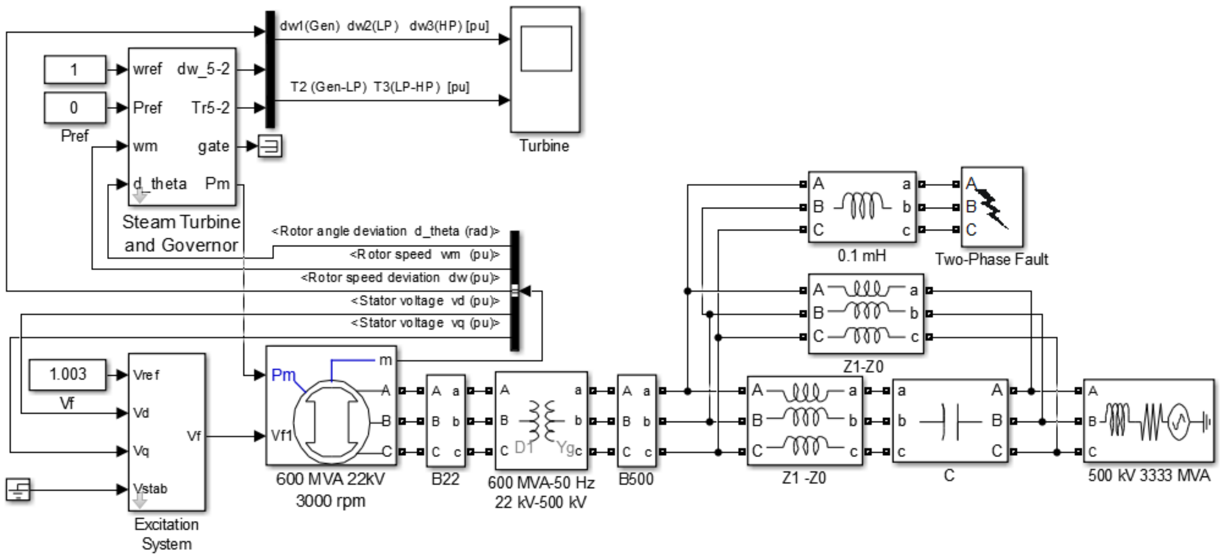

Figure 4. Power system Matlab model in case with AVR.

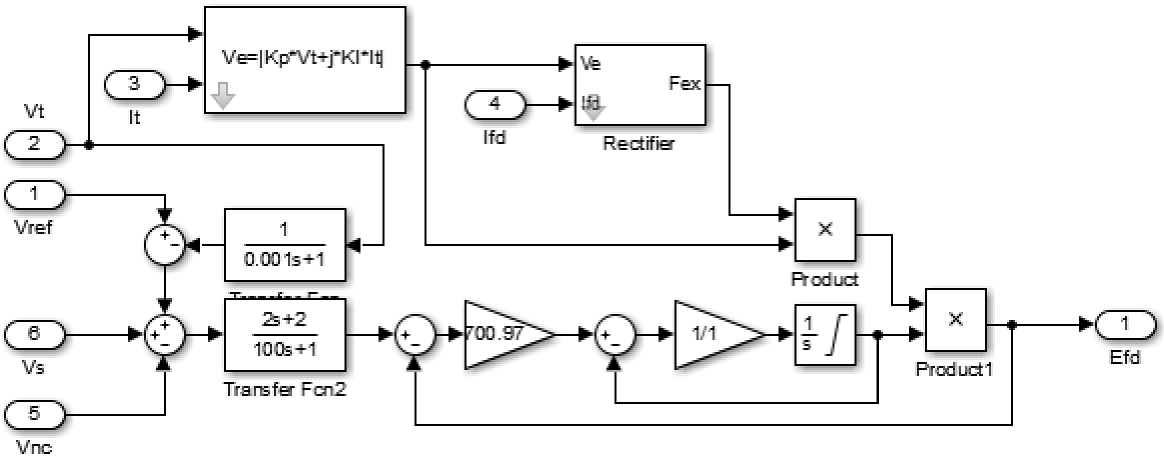

Figure 5. AVR model.

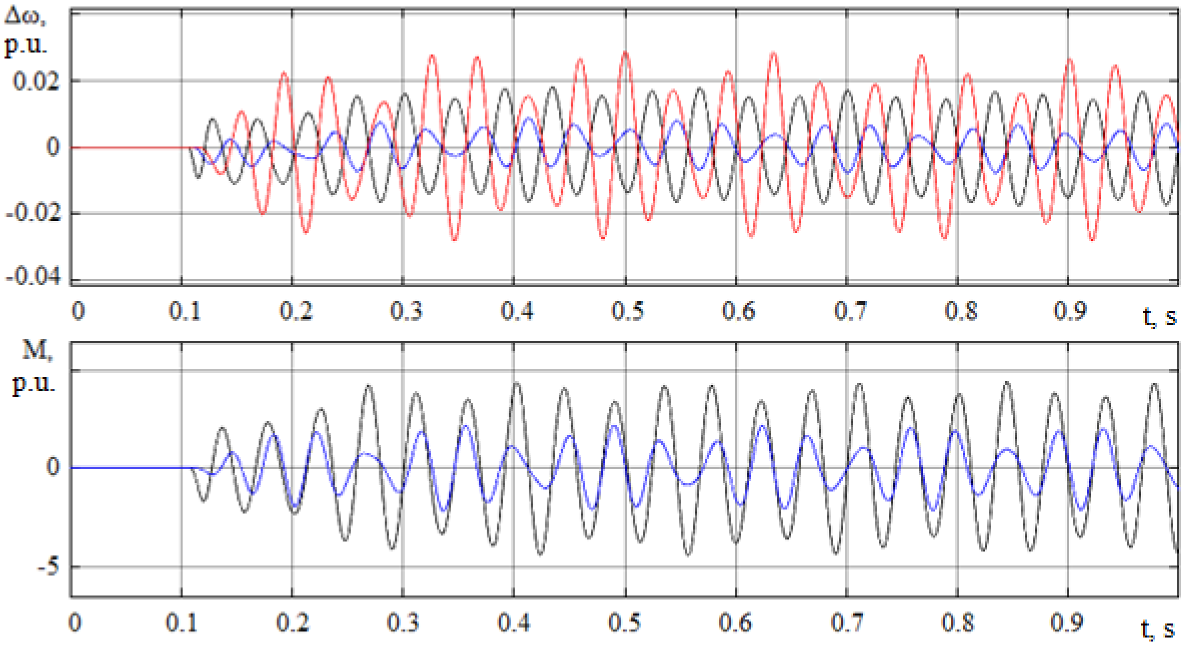

Figure 6. Time diagrams of the angular velocities deviations and torsional moments for the case with AVR at the level of series compensation μ = 0.5.

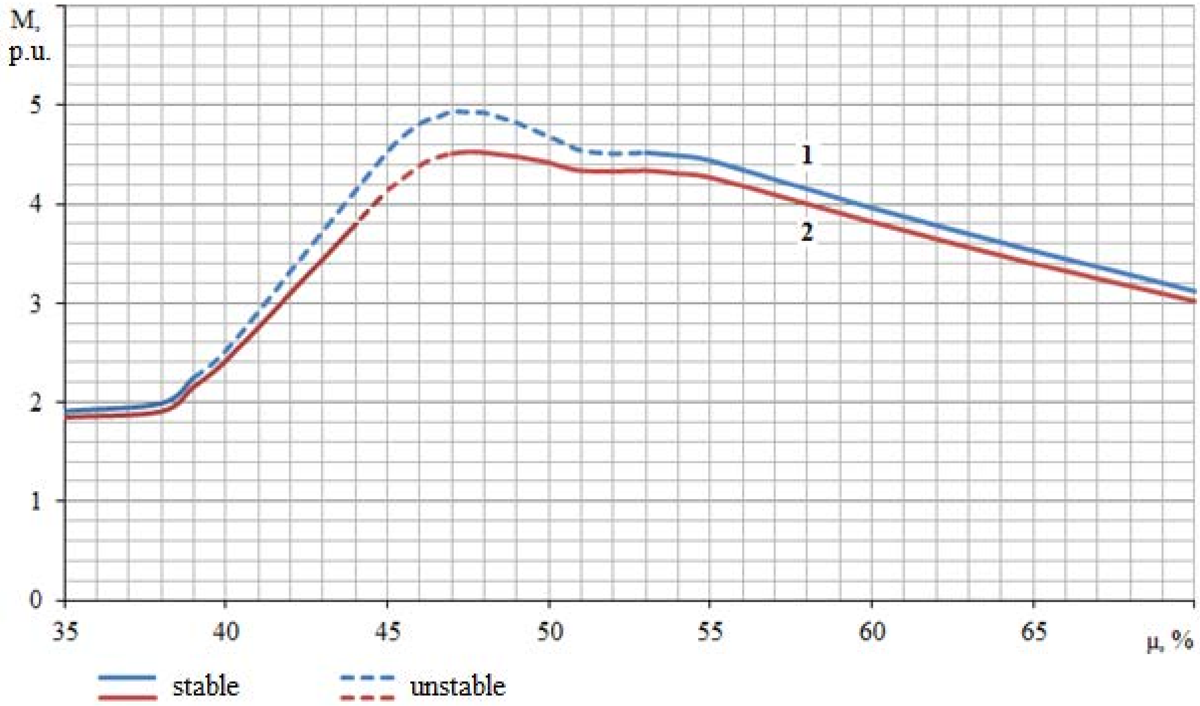

Figure 7. Comparison of torsional moment amplitudes for the cases without AVR (1) and with AVR (2) at different levels of series compensation μ.

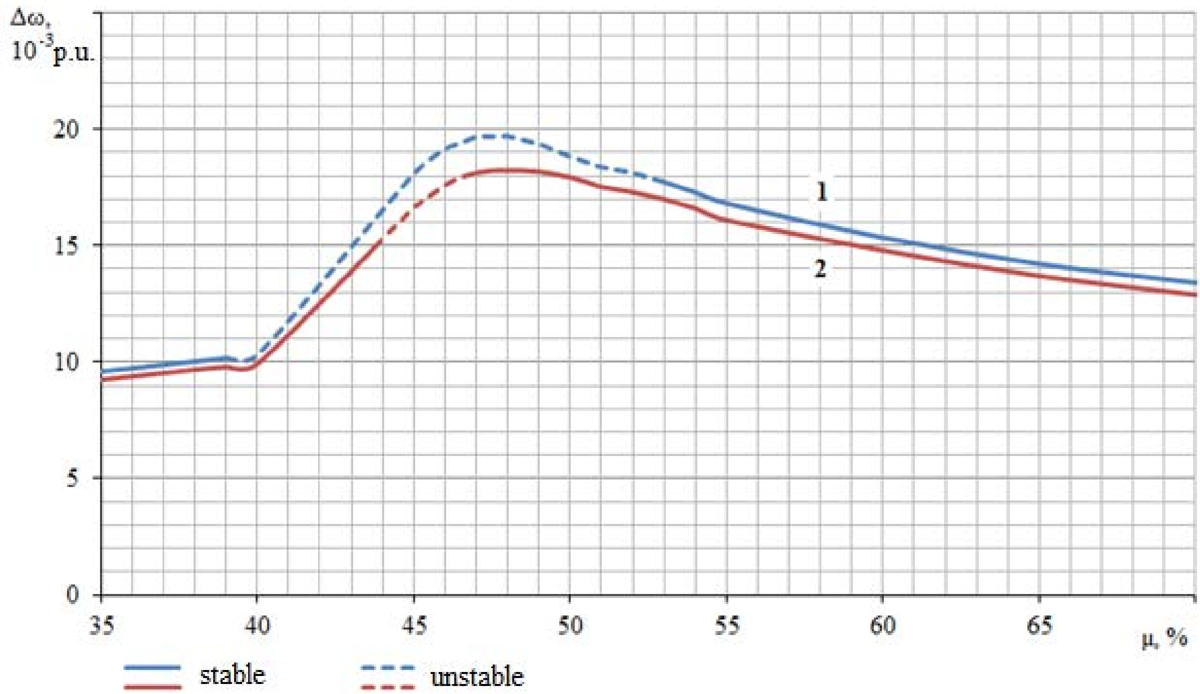

Figure 8. Comparison of the angular velocity deviation amplitudes for the cases without AVR (1) and with AVR (2) at different levels of series compensation μ.

5. Discussion

When the excitation control system is introduced (figure 4) the results did not change qualitatively. Attempts to use different models of AVR (figure 5), as well as the variation of the settings of such systems reduce the oscillations amplitudes (figure 6). Comparison of maximum amplitudes of angular velocity deviations and torsional moments of mechanical subsystem for models without AVR and with AVR (figures 7, 8) with indication of areas in which oscillations are increase, showed slight reduction of oscillation amplitudes and significant reduction of the oscillation development zone. In figure 9 the time diagrams of the generator angular velocities deviations for models without AVR and with AVR at the level of longitudinal compensation μ=0.5 are shown.

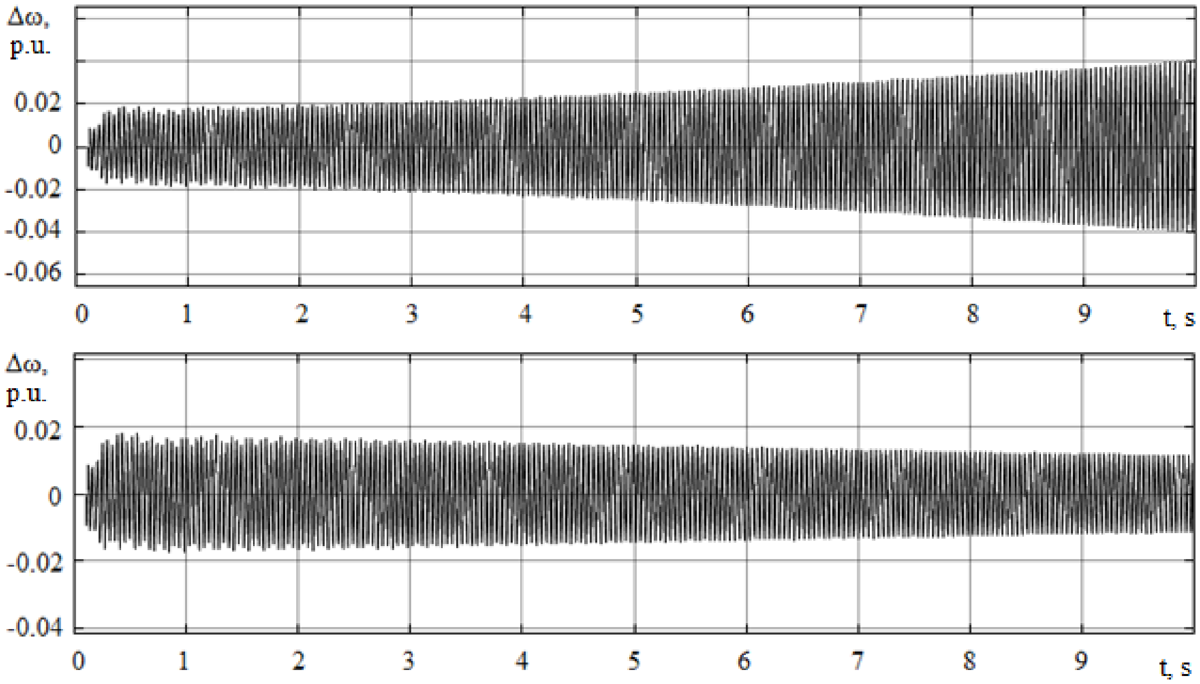

Figure 9. Evolution of torsional vibrations for the cases without AVR and with AVR with the same value of the series compensation level μ = 0.5.

6. Conclusion

The AVR has an influence on the transients in the turbogenerator, reducing the amplitude of oscillations in the mechanical subsystem. According to figures 7, 8 that the range of the series compensation level at which the oscillations in the system are increased is markedly reduced in the case with AVR, but is not completely disappeared. Further research assumes the use of a power system stabilizer as an additional damping element.

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