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Impact of Increased Frequency Excitation System on Stability of Synchronous Generator

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***Abstract*—The paper presents a modified classic dynamic model of synchronous generator connected to infinity bus. The model allows to use dynamic models of excitation systems containing field voltage and field current inputs for investigation of electromechanical transient processes of power system. This model was used for analysis of dynamic characteristics of synchronous generator with increased frequency excitation system according to small perturbation and eigenvalues methods. The influence of parameters of external electrical network on quality of transient processes is estimated. The transfer function of the synchronous generator with increased frequency excitation system is explored according to eigenvalues analysis method. According to the suggested methodic, stability margins of Lithuanian power plant are evaluated for different operating conditions of the generator.**

***Index Terms*—Automatic voltage control, eigenvalues and eigenfunctions, power system dynamics, power system stability.**

I. INTRODUCTION

The quality of fast electromechanical transient processes control in power systems mostly depends on proper operation of excitation systems and automatic voltage regulators of synchronous machines. Numerical simulation of operating conditions of power systems requires analysis of models of generating units and their regulators.

In this paper, characteristics of the increased frequency excitation system dynamic model [1] are analyzed as well as their influence on stability of the synchronous generator connected to infinity bus. The Heffron-Phillips model (HPM) of a synchronous machine [2], [3] is used for the research of dynamic characteristics of the synchronous generator. The HPM model is a linearised model of the synchronous generator, where the amortisseur effects, armature resistance and the stator transformer voltage are neglected. Because of the simplicity, this model allows analytical analysis of the generating unit's behavior.

II. DYNAMIC MODEL OF SYNCHRONOUS GENERATOR WITH ALTERNATING CURRENT EXCITATION SYSTEM

In order to investigate the influence of the increased frequency excitation system model parameters on synchronous generator dynamic and steady-state periodical stability conditions, the dynamic model of the generating unit should be composed. Dynamic behavior of the synchronous generator operating in the electrical network of infinite power [3] is described following:

$$\frac{\mathrm{d}\,\Delta\omega}{\mathrm{d}\,t} = \frac{1}{2H}\left(\Delta T_{\mathrm{m}} - \Delta T_{\mathrm{e}} - D_{\mathrm{S}}\Delta\omega\right), \tag{1}$$

$$\frac{\mathrm{d}\,\Delta\delta}{\mathrm{d}\,t} = \omega_0 \Delta\omega, \tag{2}$$

$$\Delta T_{\mathrm{e}} = K_1\Delta\delta + K_2\Delta\psi_{\mathrm{fd}}, \tag{3}$$

$$\frac{\mathrm{d}\,\Delta\psi_{\mathrm{fd}}}{\mathrm{d}t} = \frac{K_3}{T_3}\left(\Delta E_{\mathrm{fd}} - K_4\Delta\delta\right) - \frac{1}{T_3}\Delta\psi_{\mathrm{fd}}, \tag{4}$$

$$\Delta E_{\mathrm{t}} = K_5\Delta\delta + K_6\Delta\psi_{\mathrm{fd}}, \tag{5}$$

$$\frac{\mathrm{d}\,\Delta u_{\mathrm{C}}}{\mathrm{d}\,t} = \frac{1}{T_{\mathrm{R}}}\left(\Delta E_{\mathrm{t}} - \Delta u_{\mathrm{C}}\right), \tag{6}$$

$$\Delta E_{\mathrm{fd}} = G_{\mathrm{ex},u}\left(\Delta V_{\mathrm{REF}} - \Delta u_{\mathrm{C}}\right) + G_{\mathrm{ex},i}\Delta i_{\mathrm{fd}}, \tag{7}$$

where ω_0 and $\Delta\omega$ are the generator rotor synchronous angular speed and speed deviation; $\Delta\delta$ is the rotor angle deviation; ΔT_{m} and ΔT_{e} are the mechanical and electrical torque deviations; $\Delta\psi_{\mathrm{fd}}$ is the field flux deviation; ΔE_{t} and ΔE_{fd} are the generator terminal voltage and field voltage deviations; Δu_{C} is the automatic excitation control input signal deviation; H is the generating unit inertia constant; D_{S} is the load damping coefficient; $G_{\mathrm{ex},u}$ and $G_{\mathrm{ex},i}$ are the components of the excitation system transfer function; ΔV_{REF} is the excitation reference signal deviation; Δi_{fd} is the generator field current deviation; K_1, K_2, K_3, T_3, K_4, K_5 and K_6 are the parameters dependent on generator operating conditions and external electrical network impedance [3]; T_{R} is the time constant of the terminal voltage transducer.

The linear model described by the equations (1) to (7) is a modified Heffron and Phillips dynamic model of the synchronous generator operating in the electrical network of infinite power. The suggested modified model accounts the field current signal and is suitable for investigation of synchronous machines with alternating current excitation systems.

A detailed block diagram of the analyzed increased frequency excitation system dynamic model [1] is presented in Fig. 1. The model is linearized in order to simplify parameters estimation technique. It is assumed that the object's operating parameters varies in the linear operating zone. Therefore, the relationship between excitation system

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output and inputs is described following:

$$u_{\mathrm{fd}} = \frac{K_{\mathrm{A}}}{1+sT_{\mathrm{A}}} \cdot \frac{C + sK_{\mathrm{N}}T_{\mathrm{E}}}{\left(K_{\mathrm{E}} + S'_{\mathrm{E}}\right) + sT_{\mathrm{E}}} \cdot \left(u_{\mathrm{REF}} - u_{\mathrm{C}}\right) + \left(K_{\mathrm{D}} \cdot \frac{C + sK_{\mathrm{N}}T_{\mathrm{E}}}{\left(K_{\mathrm{E}} + S'_{\mathrm{E}}\right) + sT_{\mathrm{E}}} + \left(K_{\mathrm{I}} - D\right)\right) \cdot i_{\mathrm{fd}}, \tag{8}$$

where u_{fd} is the main generator field voltage; u_{REF} is the reference voltage; u_{C} is the generator terminal voltage behind the transducer; i_{fd} is the field current; K_{A}, T_{A}, K_{N}, T_{E}, K_{E}, K_{D} and K_{I} are the parameters of the increased frequency excitation system dynamic model, S_{E}', C, D are the parameters of the linearised nonlinear components of the model.

The transfer function (8) of the increased frequency excitation system is added to the composed HPM model (1)–(7) in order to investigate the generating unit's dynamic characteristics. While the transients are perturbed by the small signal, it can be assumed that the excitation system and the synchronous generator operate in linear zone. The composed model of the synchronous generator with increased frequency excitation system (Fig. 2) allows investigation of the synchronous machine's rotor speed and angle, generating electrical power, terminal voltage, field flux linkage and excitation voltage dynamics. Transient processes can be disturbed by changing the input signals, the first of which is the excitation reference deviation ΔV_{REF} and the second is the mechanical torque deviation ΔT_{m}. In order to study the influence of the excitation system parameters on generating unit's dynamics the suggested model was described by the general transfer function $W(s)$ of the 9$^{\text{th}}$ order, the input of which is the excitation reference signal deviation ΔV_{REF} and the output is excitation signal deviation ΔE_{fd}:

$$\Delta E_{\mathrm{fd}} = W(s)\,\Delta V_{\mathrm{REF}}. \tag{9}$$

Transfer function parameters depend on excitation system model parameters and parameters K_1, K_2, K_3, T_3, K_4, K_5 and K_6.

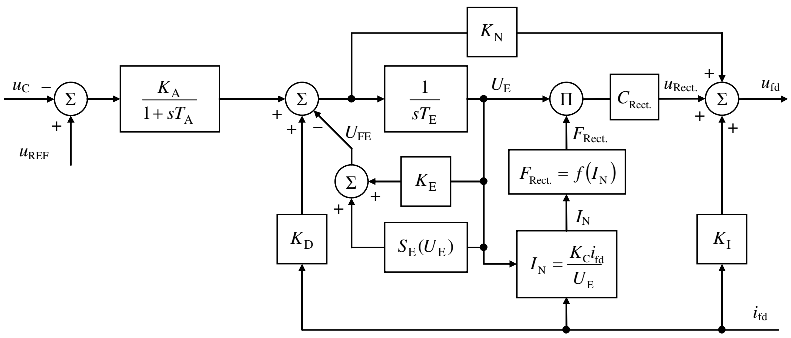


Fig. 1. Block diagram of increased frequency excitation system model [1].

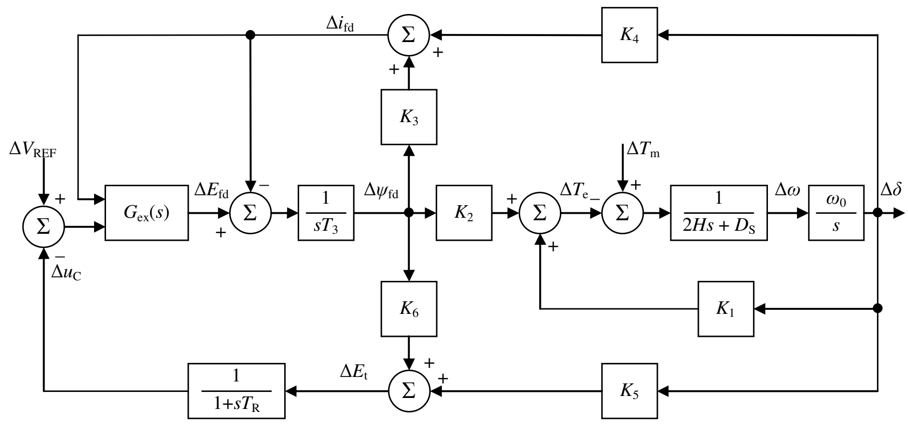


Fig. 2. Linear model of synchronous generator operating in the power system of infinite power.

III. STABILITY ANALYSIS OF SYNCHRONOUS GENERATOR WITH INCREASED FREQUENCY EXCITATION SYSTEM

A. Characteristic of Lithuanian power plant

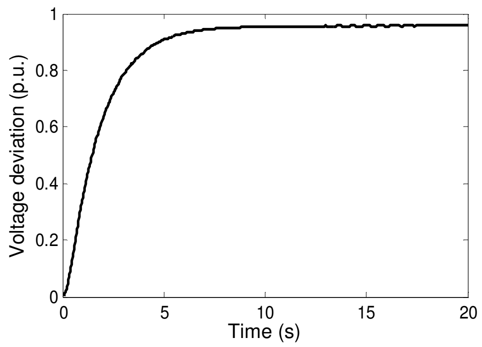
The increased frequency excitation systems were developed in Soviet Union. Though some of such excitation systems are changed into static excitation systems, original ones are used in few power plants to date. In Lithuania, the increased frequency excitation systems were installed in Lithuanian power plant. There were three generating units of 150 MW and three units of 300 MW capacities with the increased frequency excitation systems originally installed in the power plant, while other one unit of 150 MW capacity was equipped with static excitation system and other one unit of 300 MW capacity was equipped with brushless excitation system. Presently, the increased frequency excitation systems of 300 MW units were reconstructed and only the one 150 MW unit (unit No. 2) is equipped with the high frequency excitation system in Lithuanian power plant. However, the continuous operation of this unit gives opportunity to investigate its performance and increases relevance of its stability analysis.

Lithuanian power plant is connected to 330 kV power grid through six transmission lines. For using the HPM model, the equivalent of the external electrical network was calculated. Three cases were analysed: on-peak load conditions (it is assumed to be rated conditions), off-peak load conditions and the worst theoretical case when the generating unit operates through the single line.

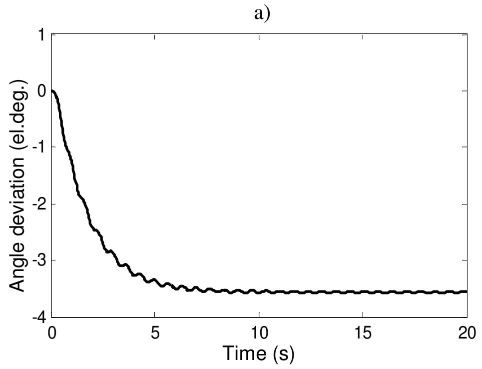
B. Stability analysis

The composed model was used for the investigation of characteristics of dynamic behavior of the generating unit No. 2 of Lithuanian power plant. Small signal stability analysis allows simulate transients of the linearized model [4]. The analysis shows if the generator operates at rated conditions ($P_* = 1$; $Q_* = 0.85$; $U_* = 1$, where P_* and Q_* are the active and reactive output power in p.u. based on rated active power and U_* is the terminal voltage in p.u.) and the reference signal deviation ΔV_{REF} is supplied to the excitation system input, the transients of the generator terminal is damped after 10 s (Fig. 3).

The quality of dynamic characteristics of the model of synchronous generator with increased frequency excitation system is characterized by eigenvalue analysis [5], [6] of the transfer function. The transient process of the operating parameters is similar to monotonic and is described by real eigenvalues (Fig. 4 and Table I). Small damped oscillations of $f = 1.503$ Hz depend on the poles equal $-0.1504345\pm j9.4434$. These eigenvalues depend mostly on operating conditions and excitation system parameters. Also, the imaginary pair of eigenvalues equal to $\pm j9.5183$ exists. This pair of eigenvalues causes undamped oscillations. The oscillations amplitude is very small and can be neglected during generating unit's real operating conditions. The imaginary pair of the poles does not depend on excitation system model parameters.



a)



b)

Fig. 3. Generator terminal voltage (a) and rotor angle (b) response to the excitation reference signal deviation of 1 p.u.

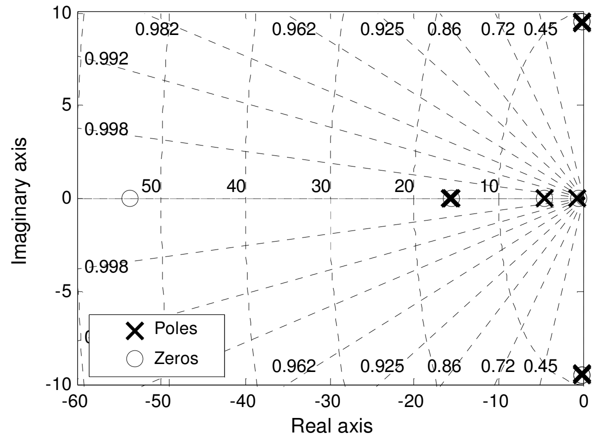


Fig. 4. Zero-pole diagram of synchronous generator with increased frequency excitation system model transfer function under rated operating conditions.

TABLE I. CHARACTERISTICS OF ZEROS AND POLES OF SYNCHRONOUS GENERATOR WITH INCREASED FREQUENCY EXCITATION SYSTEM MODEL TRANSFER FUNCTION UNDER RATED OPERATING CONDITIONS.

	Value	Damping	Damped frequency, rad/s
Poles	-15.701	1.0000	0
	-15.504	1.0000	0
	±j9.5183	0	9.5183
	-0.1504345±j9.4434	0.0159278	9.4436
	-4.6232	1.0000	0
	-4.5375	1.0000	0
	-0.62737	1.0000	0
Zeros	-53.803	–	–
	-15.5039	–	–
	±j9.5183	–	–
	-0.148148 ±j9.5091	–	–
	-4.6232	–	–
	-0.51505	–	–

The steady-state periodical stability conditions of the synchronous generator with increased frequency excitation system during on-peak load and off-peak conditions and working through the single line are investigated. The stability margins can be derived by using the HPM model and observing the oscillations of operating parameters or by analyzing the eigenvalues of the transfer function (9). The maximum permissible power according to the steady-state periodical stability conditions was evaluated for the terminal voltage range from 0.95 to 1.05 p.u. (Fig. 5).

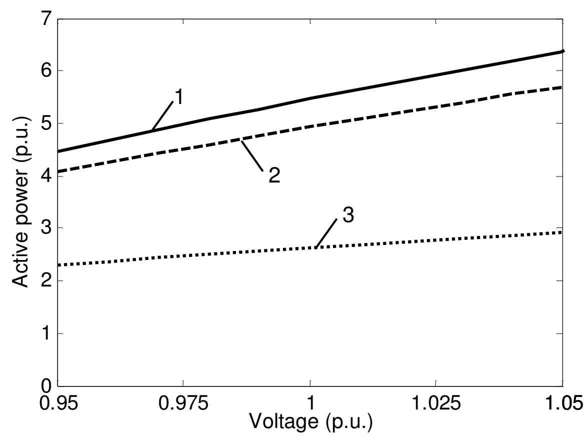


Fig. 5. Steady-state periodical stability limits: 1) on-peak load condition, 2) off-peak load condition, 3) working through single line.

Also, the security margin factors for active power were evaluated. Depending on the terminal voltage, the security margin factors varies from 0.693 to 0.861 under on-peak load conditions, from 0.677 to 0.844 under off-peak load conditions and from 0.492 to 0.689 when operating through the single line. As the security margin factors for active power should be at least 0.20 under normal operation and 0.08 under restorative conditions [7], the estimated security margin factors of the generator are sufficient under all operating conditions.

C. Sensitivity of stability conditions on parameters of increased frequency excitation system

It is determined that the steady-state periodical stability conditions [8] mostly depend on the change of the transfer function eigenvalue pair which is equal to $-0{,}1504345 \pm j9{,}4434$ under rated conditions. The dependence of this eigenvalue change on the change of the excitation system model parameters is analyzed. It is determined that values of the model parameters T_E, K_D, D and K_I make the most influence on stability margin. This means that the field current signal has significant influence on the generator stability conditions. The margins of excitation model parameters, when generator operating under rated conditions is stable, are presented in Table II.

TABLE II. MARGINS OF INCREASED FREQUENCY EXCITATION SYSTEM MODEL PARAMETERS.

	Estimated value	Minimal value	Maximum value
K_A	4.148	-0.071	120.1
T_A	0.1810	0	–
K_N	0.1641	-14.97	2.29
T_E	0.1233	0	–
$C_{Rect.}$	2.141	-0.753	8.21
K_D	1.8108	–	2.11
D	0.1610	-0.838	–
K_I	-1.3078	–	0.763

Furthermore, the sensitivity of the generator steady-state periodical stability limit to the values of the increased frequency excitation system parameters is evaluated. The sensitivity is expressed by the ratio of maximum permissible power according to the steady-state periodical stability change ΔP_{max*}, in p.u., and the parameter change $\Delta \Pi$ (Table III). The values of parameters K_A, C, K_N, D and K_I have the most significant influence on the stability limit, e.g. if the values of parameters C and K_A increases 1.01 times, the stability limit P_{max} decreases by value equal about $0.5P_N$, where P_N is the rated generator active power. If the values of parameters K_N, D and K_I increase 1.01 times, the stability limit decreases more than $0.3P_N$.

TABLE III. SENSITIVITY OF STEADY-STATE PERIODICAL STABILITY LIMIT OF SYNCHRONOUS GENERATOR TO THE VALUES OF INCREASED FREQUENCY EXCITATION SYSTEM PARAMETERS

Parameter	$\Delta P_{max*}/\Delta \Pi$
K_A	-0.529
T_A	-0.287
K_N	-0.375
T_E	-0.1243
$C_{Rect.}$	-0.506
K_D	-0.253
D	-0.335
K_I	-0.327

IV. CONCLUSIONS

The modified classic dynamic model of the synchronous generator connected to the infinitive bus is suggested for use of more complex dynamic models of excitation systems with field voltage and field current inputs.

Dynamic characteristics of the synchronous generator with increased frequency excitation system are analysed according to the small signal and eigenvalue analysis methodics. It is determined that the response of operating parameters of the synchronous generator is aperiodic containing undamped oscillations. The frequency and the magnitude of the oscillations depend on external impedance of the electrical network and on operating conditions.

The analysis shows that stability limits of the synchronous generator significantly depend on parameters of the field current loop in the model. This loop should be accounted while simulating transients of synchronous generators with alternating current excitation systems.

The small signal and eigenvalues research methods were used for the dynamic qualities of the synchronous generator with increased frequency excitation system investigation. Analysis was performed for Lithuanian power plant where the generating unit with increased frequency excitation system is installed. The determined security margin factors for active power of the generating unit varies from 0.492 to 0.861 depending on operating conditions and are higher than the lowest permissible value which is equal to 0.20.

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