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Identification of Dynamic Model of Synchronous Generator High Frequency Excitation System

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Introduction

Study of power system (PS) stability and electromechanical transient processes is needful for the generating units load control and power reserve forecasting, lines disconnection for maintenance schedule, automatic protection design and supervisory control coordination. Precision of power system steady-state and transient stability analysis depends on the accuracy of usable power system elements models. Incorrect determination of stability margins may cause emergency conditions in the power system, otherwise, if determined stability conditions are smaller than real, power system operation would be uneconomical. The most influence onto transient processes depends on the generating units and their excitation systems and turbine speed governor operation [1]. The data of excitation systems designed in the Soviet Union are not sufficient for accurate excitation system models. It is necessary to create excitation systems' testing and model parameters identification methodology.

Dynamic model identification methodology

The object's static and dynamic characteristics, static and dynamic nonlinearities and characteristics' sensitivity to operating parameters must be accounted while identifying the dynamic object. The model structure is composed by using theoretical studies, and the parameters are estimated from test data. Usually power system dynamic model structures are known and can be described by linear or nonlinear differential equations. The task of identification is to determine the model parameters numerical values. The parametric identification methods are used for identification of dynamic models in power system transient investigation [2, 3]. The task of identification in time domain is determination of transient function between input and output signals

$$y(t) = G(q,\theta)\,u(t) + H(q,\theta)\,e(t); \tag{1}$$

here q – shift operator; θ – transfer function parametric vector; $e(t)$ – sequence of random unrelated data.

The parameters θ_g and θ_h of discrete generalized parametric model partial cases response functions $G(z, \theta_g)$ and $H(z, \theta_h)$ are identified using sampled input and output signals $u(t)$ and $y(t)$. The main transient function $G(z, \theta_g)$ of identified discrete model is converted into continuous time domain transient function $\hat{W}(s, \hat{\theta})$. The parametric vector $\hat{\theta}$ of the continuous time model is determined from

$$\hat{\theta} = \arg\min_{\theta} \sum_{i=0}^{n-1} \big(y(t+1) - \hat{y}(t+1), \theta\big)^2 . \tag{2}$$

The identified model must meet three similarity conditions:

- The autocorrelation of measured and simulated identified transfer function output signals must be near 1, and the least square criterion must be as small as possible.
- Degree of determined transfer function polynomials must be equal or close to the degree of polynomial of the known transfer function.
- Parameter vector members of identified continuous time transfer function must be equal or close to the members of known transfer function parameter vector.

Dynamic model of high frequency excitation system

The high frequency excitation system (Fig. 1) consists of alternating current high frequency exciter and two three-phase semiconductor rectifier bridges connected in series. The exciter is inductor type three-phase 500 Hz self-excited synchronous generator all windings of which are fitted on stator. The main field winding L_1 is consequently connected with the main generator field winding. The windings L_2 and L_3 are regulating windings and regulating currents i_2 and i_3. Regulating currents vary depending on the main generator terminal voltage deviation ΔU_G. Automatic excitation controller consists of magnetic amplifiers MA2 and MA3. The OEL block represents over excitation limiter. The structure of high frequency excitation system model is created considering to the excitation system construction and operation [4].

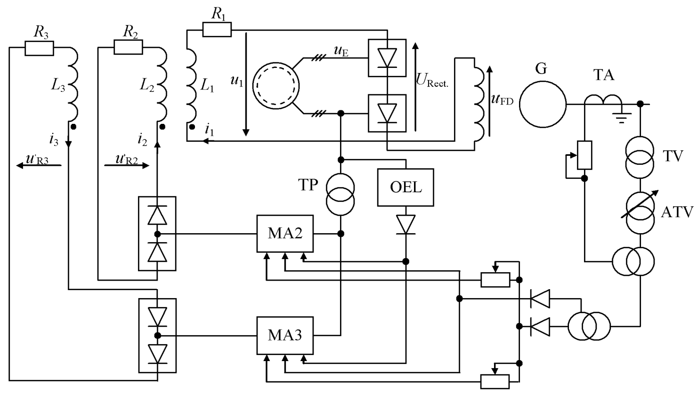


Fig. 1. High frequency excitation system circuit diagram

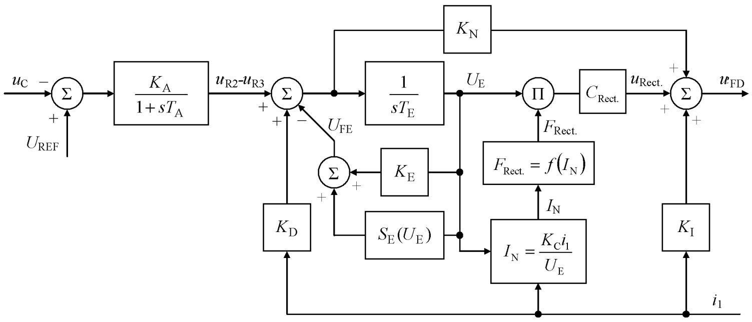


Fig. 2. Block diagram of high frequency excitation system model

A block diagram of the excitation system dynamic model is created (Fig. 2). The model input signals are reference voltage u_{REF} and generator terminal voltage u_{C} difference and field current i_1, and the output is the main generator field voltage u_{FD}.

The high frequency excitation system 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.

If the exciter working point is in the linear or near linear zone, the saturation function can be neglected or assumed to be constant.

Assuming that the rectifier load current changes insignificantly, the output characteristic of rectifier bridge is described as $F_{\text{Rect}} = c - d \cdot i_{\text{N}}$. In this case rectifier output voltage u_{Rect} is

$$u_{\text{Rect.}} = \frac{3\sqrt{2}}{\pi} \cdot F_{\text{Rect.}} \cdot U_{\text{E}} = C \cdot U_{\text{E}} - D \cdot i_1 . \quad (3)$$

The relationship between excitation system output and inputs is described following

$$u_{\text{FD}} = \frac{K_{\text{A}}}{1 + sT_{\text{A}}} \cdot \frac{C + sK_{\text{N}}T_{\text{E}}}{\left(K_{\text{E}} + S'_{\text{E}}\right) + sT_{\text{E}}} \cdot \left(u_{\text{REF}} - u_{\text{C}}\right) + \left(K_{\text{D}} \cdot \frac{C + sK_{\text{N}}T_{\text{E}}}{\left(K_{\text{E}} + S'_{\text{E}}\right) + sT_{\text{E}}} + \left(K_{\text{I}} - D\right) \right) \cdot i_1 ; \quad (4)$$

or

$$u_{\text{FD}} = \frac{\alpha_1 s + \alpha_0}{\beta_2 s^2 + \beta_1 s + \beta_0} \left(u_{\text{REF}} - u_{\text{C}}\right) + \frac{\mu_1 s + \mu_0}{\rho_1 s + \rho_0} i_1 ; \quad (5)$$

here α_1, α_0, β_2, β_1, β_0, μ_1, μ_0, ρ_1, ρ_0 are the coefficients of linear model transfer function polynomials: $\alpha_1 = K_{\text{A}}K_{\text{N}}T_{\text{E}}$; $\alpha_0 = K_{\text{A}}C$; $\beta_2 = T_{\text{A}}T_{\text{E}}$; $\beta_1 = T_{\text{A}}(K_{\text{E}} + S_{\text{E}}') + T_{\text{E}}$; $\beta_0 = K_{\text{E}} + S_{\text{E}}'$; $\mu_1 = T_{\text{E}}(K_{\text{I}} - D + K_{\text{D}}K_{\text{N}})$, $\mu_0 = K_{\text{D}}C + (K_{\text{I}} - D)(K_{\text{E}} + S_{\text{E}}')$, $\rho_1 = T_{\text{E}}$, $\rho_0 = K_{\text{E}} + S_{\text{E}}'$.

The linearized high frequency excitation system model, corresponding (4) equation, is shown in Fig. 3.

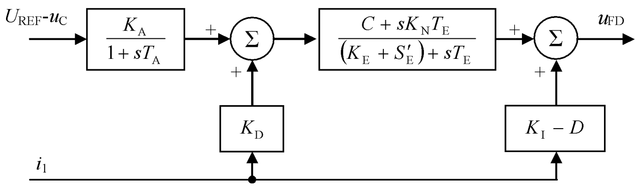


Fig. 3. Linearized high frequency excitation system model

Field test investigation

The variation of the high frequency excitation system operating parameters was monitored at Lithuanian power plant. The operating parameters' transient processes were recorded during different active and reactive generating power loads conditions.

High amplitude oscillations of operating parameters in excitation system due to short circuit were observed. Line-to-line short circuit occurred in the 330 kV line. The fault lasted 0.08 s and was cleared after 4 periods. Excitation system controller input voltage (Fig. 4) decreases proportionally to the generator terminal voltage during the fault. The significant short time exciter AC voltage and rotor DC voltage drop is observed (Fig. 5). This phenomenon is caused by free current (Fig. 6) in the generator field circuit. The current component of 100 Hz inducted of unbalanced short circuit is observed.

Generating unit operating parameters before disturbances are listed in Table 1.

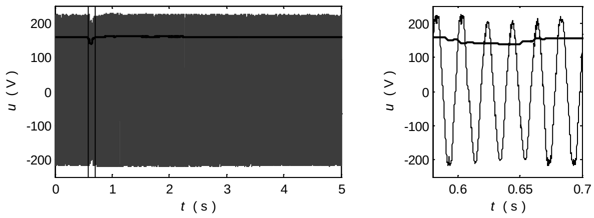


Fig. 4. Transient of excitation system controller input voltage due to short circuit in line LN 307

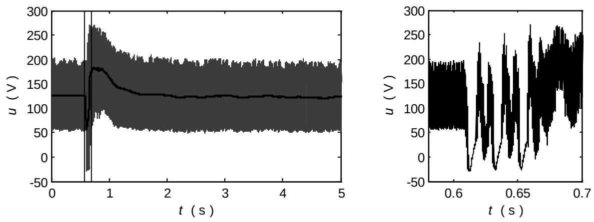


Fig. 5. Transient of generator rotor voltage due to short circuit in line LN 307

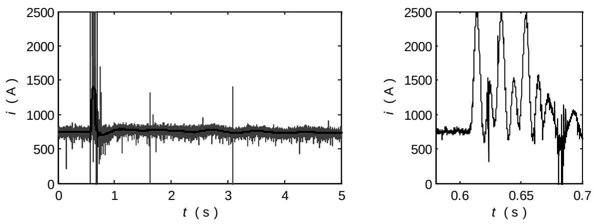


Fig. 6. Transient of generator rotor current due to short circuit in line LN 307

Table 1. Generating unit operating parameters before transients (A – line-to-line fault, B – short time voltage drop, C –voltage step increase)

Field test number	Distur-bance	P, MW	Q, Mvar	U_G, kV	U_{rot}, V	I_{rot}, A
1	A	62.2	-35.4	18.13	126.32	749.0
2	B	62.3	-26.6	18.15	113.54	664.7
3	B	61.9	65.7	18.94	260.0	1527.4
4	B	140.7	75.88	19.01	328.2	1889.4
5	B	95.5	72.63	19.05	288.0	1684.3
6	C	64.7	-12.2	18.32	138.5	823.8

Excitation system model identification and dynamic characteristics investigation

The suggested excitation system linear dynamic model parameters identification methodic is based on parameters estimation from some tests data or some transient processes. The identification sequence is:

1. A set of parametrical models transfer functions is created for the i^{th} experiment

$$\{W(s,\theta)\}_i = \{W_{i,1}(s,\theta_{i,1}), W_{i,2}(s,\theta_{i,2}), \ldots, W_{i,m}(s,\theta_{i,m})\}_i, \; i=\overline{1,n}; \quad (6)$$

here m is the number of identified transfer functions for the i^{th} experiment; n is the number of experiments.

Each identified transfer function of the i^{th} experiment must meet the first and the second similarity conditions.

2. Only one function $W_i(s,\theta_i)$ from the each transfer function set $\{W(s,\theta)\}_i$ is chosen in such way, that a sum of parameter vector dispersion is minimal

$$\sum_{p=1}^{r} D_{\theta_i} = \frac{1}{n}\sum_{p=1}^{r}\sum_{i=1}^{n}\left(\theta_{i,p} - \bar{\theta}_p\right)^2 \to 0\,; \quad (7)$$

here $\theta_{i,p}$ is p^{th} parameter of i^{th} experiment identified transfer function: $\theta_{i,p} = \{\alpha_{i,0}, \alpha_{i,1}, \beta_{i,0}, \beta_{i,1}, \beta_{i,2}, \mu_{i,0}, \mu_{i,1}, \rho_{i,1}, \rho_{i,0}\}$; $\bar{\theta}_p$ is a mean of p^{th} parameter.

3. The transfer function $W(s,\bar{\theta})$, the parameters vector $\bar{\theta}$ members of which are equal to the mean of the i^{th} experiment transfer function parameter vectors θ_i members, is established. The identified transfer function of high frequency excitation system linear model is

$$\begin{cases} W_{u_{\text{REF}}-u_{\text{C}}}(s) = \dfrac{\bar{\alpha}_1 s + \bar{\alpha}_0}{\bar{\beta}_2 s^2 + \bar{\beta}_1 s + \bar{\beta}_0}, \\ W_{i_1}(s) = \dfrac{\bar{\mu}_1 s + \bar{\mu}_0}{\bar{\rho}_1 s + \bar{\rho}_0}. \end{cases} \quad (8)$$

4. The operating point of the bridge rectifiers is determined and the coefficients C and D are calculated.

5. The parameters K_A, T_A, K_E+S_E', T_E, K_D, K_N and K_I–D of the excitation system are determined.

6. It is verified if the identified model output signal matches the measured excitation system output signal.

The parameters of high frequency excitation system model are identified according to the suggested methodic. The discrete time parametric output-error model is used for identification. The sets of transfer function $\{W(s,\theta)\}$ are composed for each transient process by using parametric OE model. The coefficients of the chosen transfer functions according to (7) condition are listed in Table 2. The members of the averaged transfer function $W(s,\bar{\theta})$ parameter vector are estimated (Table 3).

Table 2. Parameters of identified transfer functions

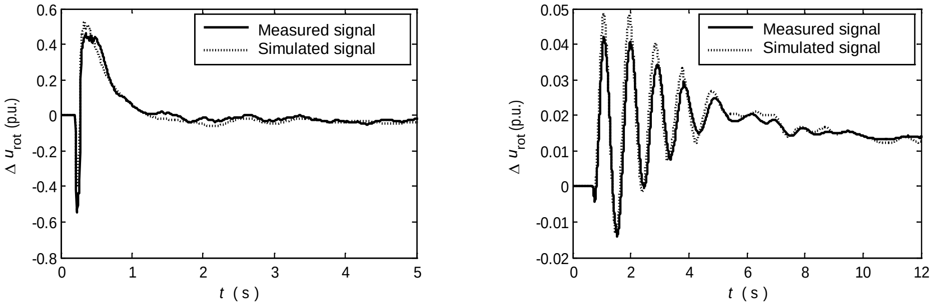
Field test No.	Transfer function parameters								
	α_1	α_0	β_2	β_1	β_0	μ_1	μ_0	ρ_1	ρ_0
1	0.035	9.32	0.040	0.408	1	-0.403	2.74	0.237	1
2	0.279	0.682	0.022	0.171	1	-0.167	1.94	0.078	1
3	0.059	8.00	0.015	0.212	1	-0.134	2.47	0.044	1
4	0.029	15.88	0.024	0.371	1	-0.022	2.29	0.036	1
5	0.070	12.38	0.030	0.264	1	-0.010	2.71	0.043	1
6	0.039	7.03	0.010	0.267	1	-0.152	2.28	0.195	1

Table 3. Parameters of the averaged transfer function

α_1	α_0	β_2	β_1	β_0	μ_1	μ_0	ρ_1	ρ_0
0.0857	8.8813	0.0241	0.2828	1.000	-0.1484	2.4090	0.1059	1.000

The optimization algorithm is used to find the model parameters. Estimated high frequency excitation system model parameters are listen in Table 4.

Precision of high frequency excitation system dynamic model parameters and efficiency of suggested identification methodic are verified.



a) b)

Fig. 7. Comparison of measured and simulated excitation system output signals transients: a) experiment No. 1, R = 0.971; b) experiment No. 6, R = 0.953

Table 4. Parameters of identified excitation system model

Parameter	Value	Parameter	Value
K_A	4.148	K_D	1.8108
T_A, s	0.1810	K_I	-1.3078
K_E	1.000	K_N	0.1641
S_E’	0.000	$C_{Rect.}$	2.141
T_E, s	0.1233	D	0.1610
K_C	0.1302		

The curves of measured excitation system transients are compared to the simulated curves, when the measured input signals are supplied into excitation system model inputs. The simulated signal matches measured one quite well in the most cases. The correlation coefficient value R exceeds 0.95 in five cases from six (Fig. 7). The correlation coefficient value R equals 0.808 only in one case from six.

Conclusions

A new model of high frequency excitation system is proposed. The created identification methodic of the excitation system dynamic model allows use the data of several transient processes and increases precision of model parameters estimation. High frequency excitation system dynamic model parameters were estimated from several transients’ data according to the created identification methodic. The efficiency of the methodic and the accuracy of the parameters were verified by comparing simulated and measured signals of the excitation system output electromotive force transients. The precision of the simulated signals exceeds 0.95 in the majority of studied cases.

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The paper presents analysis of the dynamic model of the high frequency excitation system for researches of electromechanical transient processes and stability conditions in a power system. The exciter design differs from ones that are described in most literature and suggested dynamic models may not give good results. A new model is presented and a new parameters identification technique allowing use the data of several transient processes and increasing precision of model parameters estimation is described in this study. A passive experiment was performed in Lithuanian power plant to obtain high frequency excitation system parameters. According to the sampled data of the field tests recordings, the parameters of the excitation system model were identified. The measured and simulated transient processes are presented and compared. Ill. 7, bibl. 4, tabl. 4 (in English; abstracts in English and Lithuanian).

A. Jonaitis, J. Daunoras. Sinchroninio generatoriaus aukštadažnės žadinimo sistemos dinaminio modelio identifikavimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 1(107). – P. 25–28.

Straipsnyje analizuojamas aukštadažnės žadinimo sistemos dinaminis modelis elektros sistemos elektromechaniniams pereinamiesiems vyksmams ir stabilumo sąlygoms tirti. Šios žadinimo sistemos konstrukcija skiriasi nuo aprašytų literatūroje, todėl naudojant esamus dinaminius modelius galima gauti nepakankamai tikslius rezultatus. Pateikiamas naujas modelis ir nauja parametrų identifikavimo metodika, leidžianti naudoti keleto pereinamųjų vyksmų duomenis ir padidinanti modelio parametrų nustatymo tikslumą. Aukštadažnės žadinimo sistemos parametrams nustatyti buvo atlikti pasyvieji eksperimentai Lietuvos elektrinėje. Naudojant eksperimentinius duomenis, identifikuoti žadinimo sistemos modelio parametrai. Pateikiamos ir palyginamos sumodeliuotų ir išmatuotų pereinamųjų vyksmų kreivės. Il. 7, bibl. 4, lent. 4 (anglų kalba; santraukos anglų ir lietuvių k.).