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TURBOGENERATOR WITH DUALINPUT POWER SYSTEM STABILISER

Summary. The paper deals with the synchronous generator equipped with a voltage regulator. The operation of a power system stabiliser is analysed. The generator model is created with the help of the system of differential-difference equations. The numerical investigations are important for voltage regulator and power system stabiliser design.

Key words: Synchronous generator, dualinput system stabiliser

1. INTRODUCTION

The synchronous generator equipped with voltage regulator and power system stabiliser can be described by set of differential and difference equations. The decision which of the equations can be treated as differential equations and which as difference ones is due to the value of discretisation time for particular state variable. In this paper the synchronous generator and voltage regulator are described by the system of differential equations. The power system stabiliser PSS 2A is described mathematically by the system of difference equations. The system of differential-difference equations for generator-exciter-stabiliser enables to investigate their work.

2. GENERATOR-ECXITER SYSTEM MODEL

The synchronous generator is equipped with an exciter and a power system stabiliser. The main parts of the excitation system are presented in Fig.1. The synchronous generator voltage influences the main exciter E operation by the PID regulator output signal. The system stabiliser (the power system stabiliser) influences the processor output with respect to the both frequency and active power (the so-called dualinput system stabiliser PSS 2A) [10]. The synchronous generator operation is often described by circuit models [1, 4, 5]. The generator circuit model leads to the system of differential equations which is usually used for the generator state analysis [6,9]. The field model can be used for the evaluation of synchronous generator parameters [2]. The generator linearity is usually advised and for assumed analysis. For the synchronous generator the equivalent currents result from the equivalent d-q circuit models [2, 4, 5, 9] as shown in Figs.2a,b. The adequate system of differential state equations for d,q-axis is as follows:

$$\frac{dI_D}{dt} = L_D^{-1}(U_D + \Omega\Psi_Q - R_D I_D), \qquad \frac{dI_Q}{dt} = L_Q^{-1}(U_Q - R_Q I_Q - \Omega^T\Psi_D), \tag{1a,b}$$

where the magnetic fluxes are defined in the form of

$$\Psi_D = L_D I_D, \qquad \Psi_Q = L_Q I_Q, \tag{2a,b}$$

and the matrix Ω [3x3] has only one non-zero element $\Omega_{1,1} = \omega$.
The matrices of inductances and resistances are defined as follows:

$$L_D = \begin{bmatrix} L_{ad}+L_\sigma & L_{ad} & L_{ad} \\ L_{ad} & L_{ad}+L_{\sigma f} & L_{ad} \\ L_{ad} & L_{ad} & L_{ad}+L_{\sigma D1} \end{bmatrix}, \quad L_Q = \begin{bmatrix} L_{aq}+L_\sigma & L_{aq} & L_{aq} \\ L_{aq} & L_{aq}+L_{\sigma Q1} & L_{aq} \\ L_{aq} & L_{aq} & L_{aq}+L_{\sigma Q2} \end{bmatrix}, \tag{3a,b}$$

$$R_D = \mathrm{diag}(R, R_f, R_{D1}), \qquad R_Q = \mathrm{diag}(R, R_{Q1}, R_{Q2}). \tag{3c,d}$$

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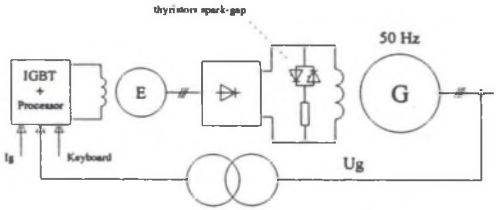

Fig.1. Excitation system for synchronous generator

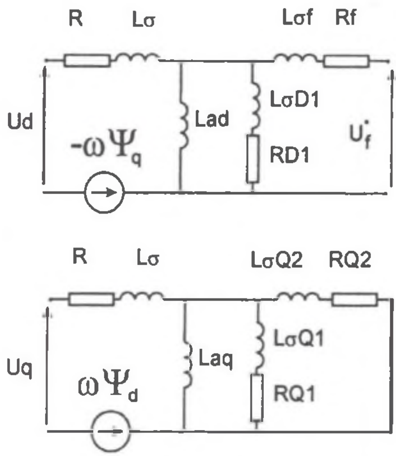

Fig.2. Equivalent circuits for d-axis and q-axis of synchronous generator

The auxiliary vectors are defined as follows:

$$I_D = \begin{bmatrix} I_d \\ I_f \\ i_{D1} \end{bmatrix}, \qquad I_Q = \begin{bmatrix} I_q \\ i_{Q1} \\ i_{Q2} \end{bmatrix}, \qquad U_D = \begin{bmatrix} U_d \\ U_f \\ 0 \end{bmatrix}, \qquad U_Q = \begin{bmatrix} U_q \\ 0 \\ 0 \end{bmatrix}. \qquad (4a,b,c,d)$$

The mechanical state equation for the synchronous machine takes the form of

$$J\frac{d\omega}{pdt} = T_e + T_m + D|\omega_{in} - \omega| = -J\frac{d^2\delta}{pdt^2}, \qquad T_e = p(\Psi_d I_q - \Psi_q I_d), \qquad (5a,b)$$

where T_e means the electromagnetic torque, D denotes the mechanical damping coefficient for the whole turbine-generator system, p means the pole-pair number.

The excitation voltage U_f for generator depends on the steering signal β as follows

$$U_f = U_{f\,max}\cos(\beta)\,. \qquad (6)$$

The steering signal β for voltage regulation systems (the so-called ARN) is accomplished by the IGBT transistor in up-to date technical solutions [7] (Fig.3.). The steering signal represents the normalised value (usually preexciter current) whose changes are limited

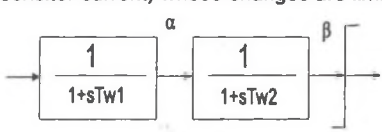

Fig.3. Equivalent block diagram of synchronous generator exciter

$$\beta = (0, \pi/2) . \tag{7}$$

The steering signal is realised by the ARN and system stabiliser (power system stabiliser) in the following way

$$\beta = \beta_1 + \beta_2 , \tag{8}$$

where β_1 means the normalised steering signal worked out by ARN, β_2 is the steering signal given by a system stabiliser:

$$\beta_1(s) = K(1 + \frac{1}{sT_I} + \frac{sT_D}{1 + sT_D / N_D})\Delta U(s) , \tag{9}$$

where ΔU means the generator voltage change, K regulator PID amplification coefficient, T_I integration time-constant, T_D differentiation time-constant, N_D inertia parameter. The system stabiliser and its output signal β_2 are mathematically described in the next paragraph.

3. SET OF EQUATIONS FOR POWER SYSTEM STABILISER

The up-to date power system stabilisers [10, 11] with two inputs are recommended to be installed at power stations on a synchronous generator whose rated power is over about 100 MW. The PSS block diagram is shown in Fig.4. The mathematical description is determined by the way of the output signal technical realisation. The system of difference equations is appropriate for the description of a system stabiliser [10].

The steering equation for the system stabiliser (shown in Fig.3) is given by

$$\frac{d\beta_2}{dt} = G(P_g, f_g) , \tag{10}$$

where α_2 means the signal component, which is worked out by the power system stabiliser. The G(P,f) function describes the output signal according to block diagram shown in Fig.4.

$$\beta_2 = S_f + S_P = S . \tag{11}$$

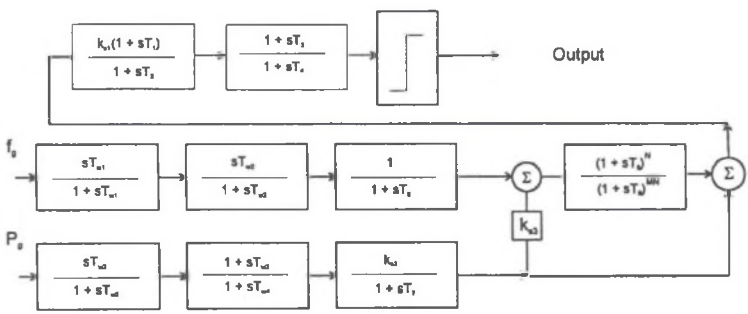

Fig. 4. System stabiliser PSS 2A with active power and frequency inputs

The difference equations for PSS, which are equivalent to the scheme presented in Fig.3, can be received basing on Laplace's (s-operator, initial zero conditions) representation in the following forms

$$S_f(s) = \frac{b_6 s^6 + ... + b_2 s^2}{a_9 s^9 + ... + a_0} f(s) , \qquad S_P(s) = \frac{(d_6 s^6 + ...) + (g_8 s^8 + ...)}{c_9 s^9 + ... + c_0} P(s) , \tag{12a,b}$$

where all the coefficients depend only on the time constants $T_1,...,T_9,T_{w1},...,T_{w4}$. The output signal of dual input stabiliser is graphically defined in Fig.3. All the constants ($T_1,...,T_9,T_{w1},...,T_{w4}$) and coefficients ($k_{s1},...,k_{s3}$) create the system of difference equations for PSS 2A. The values for all polynomials coefficients that appear in Eqns (12a,b) can be easily received by use of any symbolic calculator (Mathcad, Maple). The signals S_P and S_f mean the output signal components that depend on the generator active power P_g and frequency f_g, respectively. The inputs for PSS 2A are the generator power and frequency:

$$P_g = U(-I_d \sin(\delta) + I_q \cos(\delta)), \qquad f_g = \omega / 2\pi . \tag{13a,b}$$

The mathematical model results from a technical way of realisation of a voltage regulator and PSS 2A output signals (responses). From the technical point of view [7, 9] the synchronous generator with power system stabiliser can be presented by means of the set of differential-difference equations, as follows:

1. Synchronous generator and PID regulator are described by the system of differential equations,
2. PSS 2A is described by the system of difference equations.

The decision, which of the equation should be considered as a difference equation has been taken according to the technical conditions and device parameters. Namely, the power system stabiliser gives the output signal after 4 up to 5 time constant for PSS. This fact results from the technical way of working out the output signal of power system stabiliser. The PSS has been built with a few basis blocks as shown in Fig.3. When taking into account that the measurements are taken every 10ms = 1 / 2*(50 Hz) it leads to the time delay about 0.1 s. Hence, the PSS 2A system of state equations is treated as the system ofdifference equations.

The analyses have to be carried out due to the regulation of the National Power Grid [11]. The mathematical analysis is usually made by formulating the mathematical model of the whole electrical system. The investigations lead to the answer to the following question: Do the time constants and coefficients keep proper states for the stability of the whole system ?

Finally, the results of numerical analysis are verified by the tests on power electric stations.

4. THE DATA FOR GENERATOR-EXCITER-STABILISER SYSTEM

The extended parameter set for a synchronous generator enables to calculate the resistances and reactances for d-axis and q-axis circuit (Fig.2a,b). The chosen parameters of the synchronous generator are grouped in Table1.

Table 1

Synchronous generator parameters

SYNCHRONOUS GENERATOR PARAMETERS			
Xd	1.803	$X\sigma + X_{Tr}$	0.113 + 0.15
Xq	1.727	T_j	20,7 [s]
X'd	0.203	H	8,81 [s]
X'q	0.309	DH = D/H	2,07 [MV·A·s]
X"d	0.138	GD^2	21 tm^2
X"q	0.144	Sn	117,5 MW
Td0'	13.0 [s]	In	4920 A
Tq0'	1.3 [s]	Iwn	1300 A
Td0"	0.0038 [s]	Un	13,8 kV
Tq0"	0.055 [s]	$\cos\varphi_n$	0,85

where DH = D/H denotes the ratio of damping coefficient D to kinetic energy constant H defined as follows:

$$H = \tfrac{1}{2} J \omega_{mn}^2 / S_n \tag{14a}$$

The constant T_j means the time period during that the turbine reaches the nominal speed accelerated by the torque P_n/ω_{mn} :

$$J \frac{\omega_{mn} - 0}{T_j - 0} = \frac{P_n}{\omega_{mn}} . \tag{14b}$$

Hence, the kinetic energy constant H and damping coefficient can be presented as follows:

$$H = \tfrac{1}{2} T_j \cos\varphi_n , \qquad D = \tfrac{1}{2}(DH) \cdot T_j \cos\varphi_n . \tag{14c}$$

The parameters of the synchronous generator equivalent circuits can be derived from the extended nominal parameter set. Exemplary, the resistances and inductances are as follows:

$$R_f = \frac{Z_n}{\omega_{ln} T'_{d0}} \frac{(X_d - X_\sigma)^2}{X_d - X'_d}, \qquad R_{Dl} = \frac{Z_n}{\omega_{ln} T''_{d0}} \frac{(X'_d - X_\sigma)^2}{X'_d - X''_d}, \tag{15a,b}$$

$$L_{\sigma f} = L_n (X_d - X_\sigma) \frac{X'_d - X_\sigma}{X_d - X'_d}, \qquad L_{\sigma Dl} = L_n (X'_d - X_\sigma) \frac{X''_d - X_\sigma}{X'_d - X''_d}. \tag{16a,b}$$

5. TESTS OF SYNCHRONOUS GENERATOR, REGULATOR AND STABILISER

From practical point of view the main problem is to decide whether the both voltage regulator and system stabiliser parameters are chosen correctly? It practically means that the whole system: synchronous generator- exciter- system stabiliser operates stable [12]. At power stations the most important tests of the whole generator-exciter-PSS system for generators are: the so-called softstart, the step change (up/down test) of generator voltage at the no-load state, reactive power-drop test, the system stabiliser tests.

a) b)

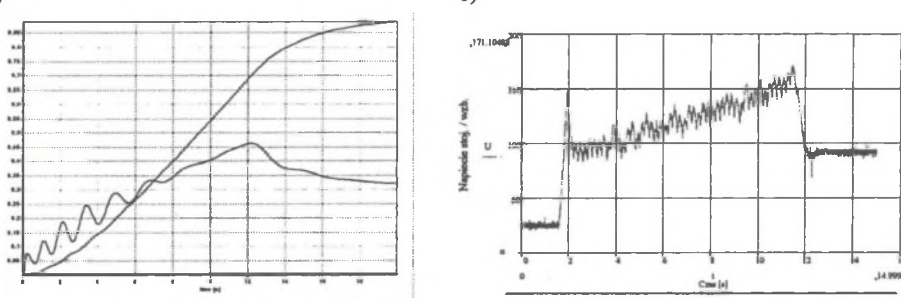

Fig.5. Softstart test. Generator voltage (smooth line) and excitation voltage (wave line) versus time – numerical test (a) and measurement (b)

The numerical simulations and tests for excitation circuits of the generator were carried out for automatic regime of regulation. The excitation voltage is shown in Fig.6.

a) b)

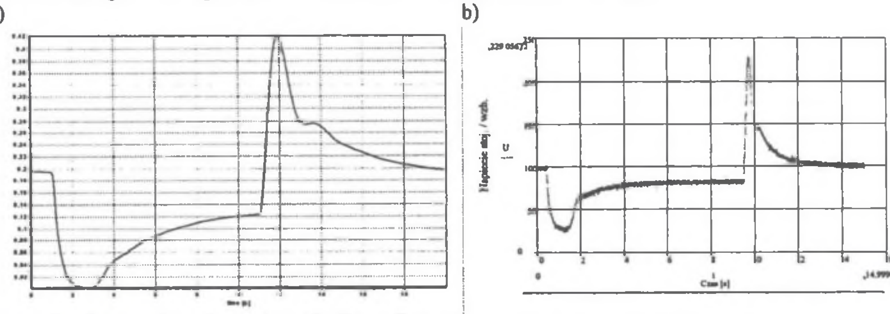

Fig. 6. Generator voltage for up/down test. Excitation voltage versus time – numerical test (a), measurements (b)

The numerical simulations for generator PSS 2A tests are presented in Fig.7. The first one is for the power system unacceptable time constants values. The second one for properly chosen PSS 2A time constants.

The presented results of numerical investigations and measurements enable to decide whether the technical solutions proposed satisfy all the defined criteria for generator operation in the National Power Grid.

a) b)

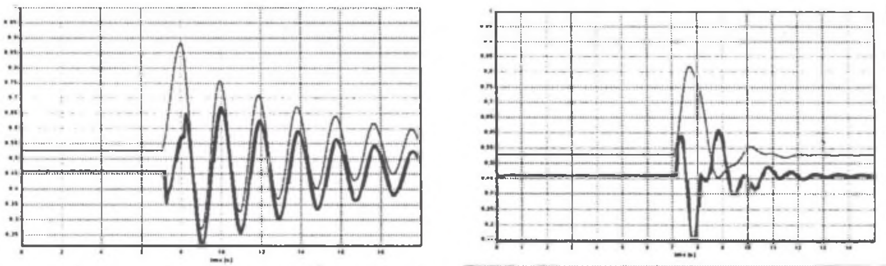

Fig. 7. Generator power stabilisation with the help of system stabiliser (hair line) and excitation voltage (bold line) versus time – the unacceptable result (on the left) and the acceptable result (on the right)

6. CONCLUSIONS

The presented model of generator – exciter – system stabiliser – from technical point of view – seems to be accurate enough. The model has been tested on the systems provided at some Power Stations in Poland and developed during the author's work at Energotest-Gdańsk Ltd. The model proposed helps one to take decision whether the generator-exciter-stabiliser can work in the national power energetic system. The comparison between numerical simulations and practical tests [9] reveal rather insignificant differences between them.

The numerical modelling can be improved by taking into account nonlinearity of a generator magnetic circuit and correction of generator parameters with the help of the field methods [2].

The numerical simulations are necessary in spite of some errors. They lead to the results which are sought at the first step of synchronous generator operation investigations.

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