11th International Research/Expert Conference
"Trends in the Development of Machinery and Associated Technology"
TMT 2007, Hammamet, Tunisia, 05-09 September, 2007.

ANALYSIS OF SHAFT TORSIONAL OSCILLATION OF LARGE TURBOGENETOR USING MATLAB/SIMULINK

Nysret Avdiu
Faculty of Computer and Electrical Engineering, University of Prishtina
Address: St. Kodra e Diellit.p.n. 10000 Prishtina Kosova
Tel: ++381 38 554 896; Fax: ++381 38 542 525
E-mail: Nysret.avdiu@fiek.uni-pr.edu

Shaban A. Buza
Faculty of Mechanical Engineering
University of Prishtina
Tel: ++381 38 554 997; Mob: ++377 44 124 315
Address: St. Kodra e Diellit.p.n. 10000 Prishtina, Kosova
E-mail: shabanbuza@fim.uni-pr.edu

ABSTRACT
Historically failures of turbine generator, rotor components due to torsionally induced high cycle vibration fatigue have been catastrophic and with little warning. The mechanical parameters which have the largest influence on the torsional strains in the shaft are the stiffness coefficients of the shaft sections and the mechanical time constants of the generator and the turbine rotors. The paper involves calculations of torsional oscillation of shaft in large turbogenerator, and for this purpose was developed mathematical model. The derived model is used for calculation of turbogenerator shaft torsional oscillation under different failure in the electrical power system. The MATLAB/SIMULINK package was developed.
Keywords: .*Turbo generator, torsional oscillation, modeling, MATLAB, SIMULINK*

1. INTRODUCTION
The number of tools suitable for transient analysis is increasing in the last few years. Besides the well-known EMTP and its variants ATP, PSCAD-EMTDC, etc, the general purpose mathematical program MATLAB is –with the introduction of the Power System, getting more and more powerful and can be used for electrical transient computations as well. The phenomenon of the torsional oscillations of it turbo-generator set which occurs during regular operation as well as at unexpected network faults, have been intensively investigated for the last 30 years, [1,2,3]. Due to torsional oscillations a number of studies has been done to explain the phenomenon and to propose preventive actions to avoid future shaft brake-downs and other associated problems. The shaft segments of turbine-generator units are exposed to large amplitude, oscillatory, mechanical stresses as a result of electric network faults, planned and unplanned switching incidents, and resonance with series compensated transmission lines. It has been identified [1,2,3] that the incidents that usually result in severe shaft stresses are line-to-line faults, three-phase faults, fault clearing, successful and unsuccessful re-closures and out of phase synchronisation. The paper involves a modelling and analysis of turbo generator set parameters which considerably influence its mechanical behaviour on the calculations of torsional strains. The analysis is carried out for a case of a three-phase short circuit at one of two parallel lines through which a generator is supplied followed by a fault clearing. The mechanical parameters which have the largest influence on the torsional strains in the shaft are the stiffness coefficients of the shaft sections and the mechanical time constants (or moments of inertia) of the generator and the turbine rotors. Maximum torsional torques is also indirectly influenced by electrical parameters of the generator.

2. SAMPLE SYSTEM STUDY

The study model is given in the Figure 1a. and consist from turbine, turbo-generator, transformers and transmission line, the rest of the network is presented as infinite bus system. The mathematical model of the system includes the shaft of a turbo generator set, described by differential equations, and mathematic modelling of electrical part, presented by modelling of synchronous generator, transformer and transmission line. The theory of the synchronous machine is well known, so only the basic model characteristics will be described here. A cross sectional view of a 3-phase, 2-pole, Figure 2 a. Salient-pole synchronous machine is modelled by conventional Park's two axis model Fig. 2.b. with one damper winding in d-axis and two damper windings in q-axis [4,5] without inclusion of the saturation effects, the air gap flux is distributed sinusoidal along the air gap, and magnetic hysteresis is negligible. Transformer and transmission lines are modelled as combination resistances and they are added to the resistance and the leakage reactance of the generator. The shaft of a turbo generator set is described by a system of differential equations. From Fig. 2.a, it can be seen that the self-inductances of the stator windings as well as the mutual inductances between the stator and rotor windings are functions of the rotor angular position. In the model used herein, Park's transformation is applied to the stator variables (voltage, current, flux linkage), which replaces the variables associated with the stator windings with variables associated with fictitious windings that rotate with the rotor. This change of variables has the effect of eliminating the angular position-dependence of the inductances. The change of variables which constitutes Park's transformation may be expressed symbolically as

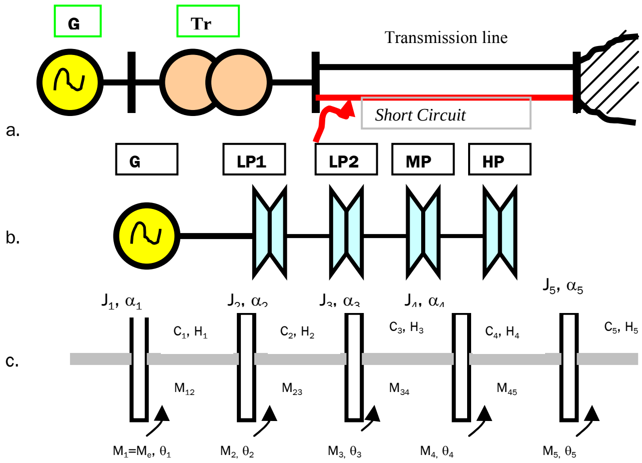

Figure 1. Sample turbine-generator, block transformers, transmission line and infinite bus system

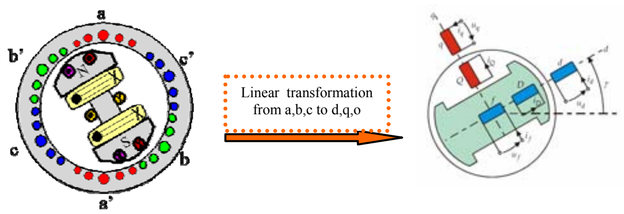

Figure 2

$$f_{qd0s}^r = K_s^r \cdot f_{abcs},\; f_{qd0s}^r = [\,f_{qs}^r\, f_{ds}^r\, f_{0s}^r\,]^T,\; f_{abcs} = [\,f_{as}\, f_{bs}\, f_{cs}\,]^T, K_s^r = \frac{2}{3}\begin{bmatrix} \cos\vartheta_r & \cos(\vartheta_r - \frac{2\pi}{3}) & \cos(\vartheta_r + \frac{2\pi}{3}) \\ \sin\vartheta_r & \sin(\vartheta_r - \frac{2\pi}{3}) & \cos(\vartheta_r + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (1)$$

Where f may be: voltage, current, or flux linkage. The superscript "r" represents that the equations are transformed to the rotor frame of reference, "s" indicates stator quantities. After transformation the generator is described by voltage equations in the d-q axes:

$$u_d = R_a i_d + \frac{1}{\omega_0}\frac{d\Psi_d}{dt} - \omega\Psi_q, \quad u_q = R_a i_q + \frac{1}{\omega_0}\frac{d\Psi_q}{dt} + \omega\Psi_d, \quad u_q = R_a i_q + \frac{1}{\omega_0}\frac{d\Psi_q}{dt} + \omega\Psi_d$$

$$u_f = R_f i_f + \frac{1}{\omega_0}\frac{d\Psi_f}{dt}, \quad 0 = R_{kd} i_{kd} + \frac{1}{\omega_0}\frac{d\Psi_{kd}}{dt}, \quad 0 = R_{kq} i_{kq} + \frac{1}{\omega_0}\frac{d\Psi_{kq}}{dt} \quad (2)$$

The electromagnetic torques of generator is:

$$m_{em} = (i_d \Psi_q - i_q \Psi_d) \tag{3}$$

Where: i_d and i_q are direct-axis and quadrature-axis currents of the generator; u_d and u_q are direct-axis and quadrature-axis voltage of the generator; i_f is field winding current of the generator; u_f is field voltage applied to the generator; i_{kd} and i_{kq} are direct-axis and quadrature-axis damper winding currents of the generator; R_a is stator winding resistance of the generator; R_f is field resistance of the generator; R_{kd} and R_{kq} damper winding resistance of the generator; ω is rotating speed of the generator; m_{em} is electromagnetic torque of the generator; J is inertia constant of the generator; Ψ_d and Ψ_q are direct and quadrature flux linkage of the generator; Ψ_f is field winding flux linkage of the generator; Ψ_{kd} and Ψ_{kq} are field direct-axis and quadrature-axis of damper winding of the generator;

The shaft system was treated as 5 disks, Fig.1b and 1c. Torsional oscillations can be described by the following system of differential equations (pu):

$$\begin{aligned}
T_1 \frac{d^2\theta_1}{dt} &= -M_1 + c_1(\theta_2 - \vartheta_1) + H_1(\frac{d\theta_2}{dt} - \frac{d\theta_1}{dt}) - \alpha_1 \frac{d\theta_1}{dt} \\
T_2 \frac{d^2\theta_2}{dt} &= M_2 + c_2(\theta_3 - \vartheta_2) - c_1(\theta_2 - \vartheta_1) + H_2(\frac{d\theta_3}{dt} - \frac{d\theta_2}{dt}) - H_1(\frac{d\theta_2}{dt} - \frac{d\theta_1}{dt}) - \alpha_2 \frac{d\theta_2}{dt} \\
T_3 \frac{d^2\theta_3}{dt} &= M_3 + c_3(\theta_4 - \vartheta_3) - c_2(\theta_3 - \vartheta_2) + H_3(\frac{d\theta_4}{dt} - \frac{d\theta_3}{dt}) - H_2(\frac{d\theta_3}{dt} - \frac{d\theta_2}{dt}) - \alpha_3 \frac{d\theta_3}{dt} \\
T_4 \frac{d^2\theta_4}{dt} &= M_4 + c_4(\theta_5 - \vartheta_4) - c_3(\theta_4 - \vartheta_3) + H_4(\frac{d\theta_5}{dt} - \frac{d\theta_4}{dt}) - H_3(\frac{d\theta_4}{dt} - \frac{d\theta_3}{dt}) - \alpha_4 \frac{d\theta_4}{dt} \\
T_5 \frac{d^2\theta_5}{dt} &= M_5 + c_5(\theta_5 - \vartheta_4) - H_4(\frac{d\theta_5}{dt} - \frac{d\theta_4}{dt}) - \alpha_5 \frac{d\theta_5}{dt}
\end{aligned} \tag{4}$$

Where is: M_1=M_e torque of generator, θ_i - torsion angles of the shaft; J - moment of inertia; T - mechanical constant, H - internal damping coefficients; c - torsional stiffness coefficients; α-external damping coefficient, index: 1-generator, 2-turbine of low pressure, 3-turbine of low pressure, 3-turbine of middle pressure, 5-turbine of high pressure, m_{12}, m_{23}, m_{24}...- torques in the coupling zones between two concentrated rotation mass, (see Fig.1.b and c).

3. SAMPLE MATLAB/SIMULINK RESULTS

MATLAB/SIMULINK is a high-performance language for technical computing that includes functions for numeric computation, data analysis, algorithm prototyping, system simulation, and application development. For the purpose of an analysis of the shaft torsional oscillation the above described mathematical model (1-4) was solved by MATLAB/SIMULINK package (Figure 3).

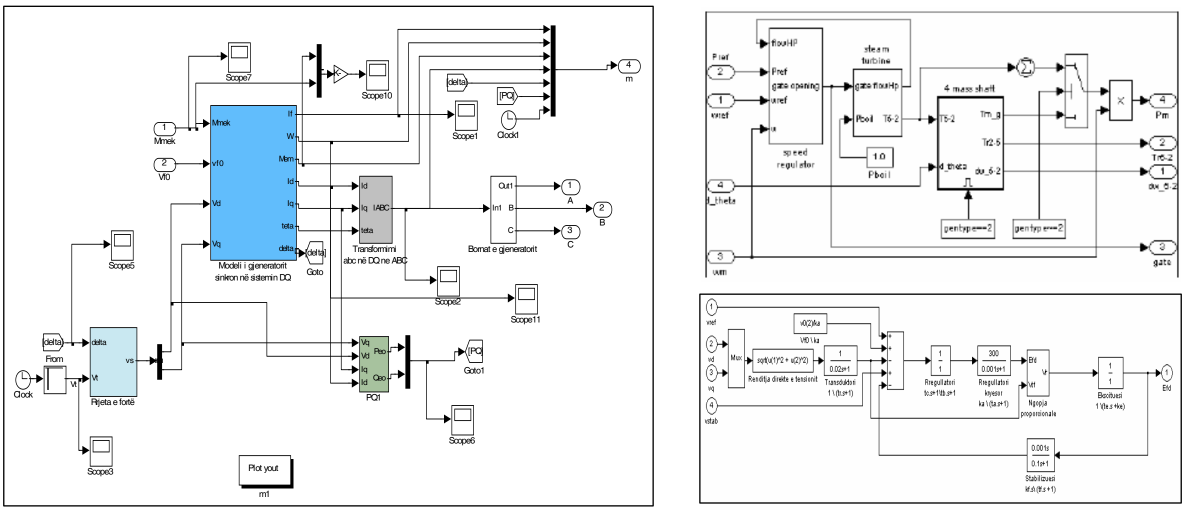

Figure 3. MATLAB/SIMULINK Unified Block Functional Model of the Sample Turbine-Generator and Infinite Bus System, System of Excitation and Steam Turbine and Shaft System

The analysis is carried out for a case of a three-phase short circuit at one of two parallel lines through which a generator is supplied followed by a fault clearing. Data used for calculation are: **Synchronous Generator**, 3 phase, round rotor: rated power P_n= 339 MW, voltage U_n= 24 kV I_n=9594 A, $\cos\varphi_n$= 0.85, n=3000 rot/min, all reactance and resitances are in pu: x''_d= 0.2232, x'_d= 0.3178, x_d= 2.253, exciter: U_{fn}=400 V, I_{fn}/I_{f0}=2490/875 A, time constant of machine: T_{d0} = 5.5 s, T'_d=1.18 s, T''_d=0.043 s, moment of inertia J_1=0.09 s 525.9 rad; **Power Transformer**, 3 phase, rated power: 400 MVA Rated Voltage: 420/24 kV, u_c= 11%, P_{Cu}=1 MW; **Transmission line** (3 phase): Length= 200 km , parameters r_l= 0.031 Ω/km, x_l=0.325 Ω/km. **Turbine and Shaft**: J_2=5913 rad, J_3=579.31 rad, J_4=157.71 rad, c_1=34.70, c_2=42.80, c_3=57, c_4=69.70, H=0.005, α=0.

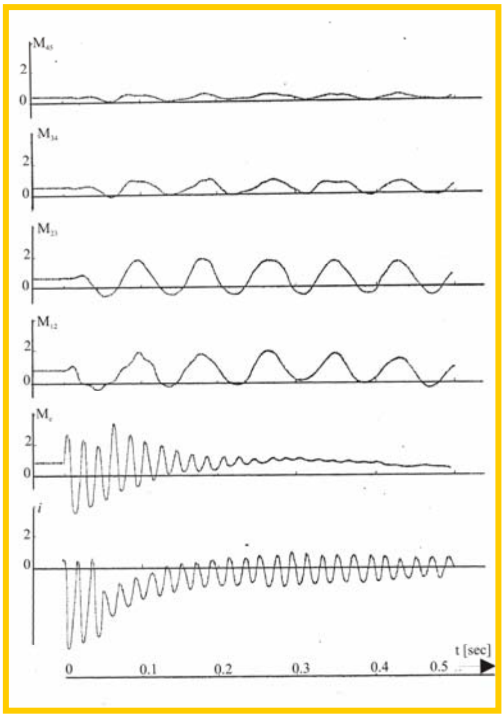

Figure 3.

Results of the torsional oscillation computation the additional program enables a direct presentation of the results in the form of the maximum torque in the coupling zone as a function of the duration fault i0.2-sec at transmission line, and clearing 0.05 sec. off the fault, Figure 4.

4. CONCLUSION

This work describes a method which illustrates the applications of MATLAB/SIMULINK for transient analysis of synchronous machines. Mathematical modelling is shortly presented. Details such as the exciter circuit, turbine and governor systems of a synchronous machine which is linked to an infinitive bus through transmission line are given and this system is implemented in SIMULINK. The extent of details in a model depends on the purpose of the study. The system equations directly provides a very interactive environment and also provides the user with easy access to the system parameters. More importantly, the computational time is significantly reduced, and thereby prompt display of the results and quick decision-making is made possible.

5. REFERENCES

[1] IEEE Subsynchronous Resonance Task Force, "First Benchmark Model for Computer Simulation of Subsynchronous Resonance", IEEE Trans. On PAS,, vol. PAS-96, pp.1565-1572, Sept./Oct. 1977.

[2] IEEE SSR Working Group, "Second Benchmark Model for Computer Simulation of Subsynchronous Resonance", IEEE Trans. On PAS,, vol. PAS-104, No.5, pp.1057-1066, May 1985.

[3] Jackson and others, “Turbine generator Shaft Torques and fatigue: Part 1-Simulation method and fatigue analysis” IEEE Trans, PAS, Nov/Dec 1979, VOV. PAS-98

[4] Yacamini, R.; Smith, K.S.; Ran, L., “Monitoring torsional vibrations of electro-mechanical systems using stator currents,” Journal of Vibration and Acoustics, Transactions of the ASME, v 120, n 1, Jan, 1998, p 72-79. 9.

[5] A.M. Sharaf, M.Z.EL-Sadek, F.N. Abd-Elbar and A.M. Hemeida, “ Global Error Driven Control Scheme for Static VAR Compensator,” *Electric Power Systems Research* , v.51, N 2, pp 131-141, August 1999. 10.

[6] A.M. Sharaf; Bo Yin; and M. Hassan, “A Novel On-line Intelligent Shaft-Torsional Oscillation Monitor for Large Induction Motors and Synchronous Generators,” *CCECE04,* IEEE Toronto, May 2004.

[7] M.R. Iravani, “Coupling phenomena of torsional modes,” *IEEE Transactions on Power Systems,* vol.4, No3, pp 881-888, August 1989.

[8] Yacamini, R.; Smith, K.S.; Ran, L., “Monitoring torsional vibrations of electro-mechanical systems using tator currents,” Journal of Vibration and Acoustics, Transactions of the ASME, v 120, n 1, Jan, 1998, p 72-79.