J. King Saud Univ., Vol. 13, *Eng. Sci.* (1), pp. 103-116 (A.H. 1421/2001)

Damping Torsional Oscillations Using Thyristor Controlled Braking Resistors

R. M. Hamouda
Electrical Engineering Department, King Saud University
P.O. Box 800 Riyadh, 11421 Saudi Arabia

(Received on 19 October 1999; accepted for publication on 04 April 2000)

Abstract. This paper presents a new method for controlling a dynamic braking resistor in power system. It allows a Thyristor Controlled Braking Resistor (TCBR) to effectively damp inertial and torsional oscillations in a large turbo-generator. The study is performed on system-1 of the second IEEE benchmark for simulation of sub-synchronous oscillations, using eigenvalue analysis and verified by detailed digital simulation. A dynamic model for the TCBR is developed. The pole placement technique is used to design the firing angle control system. The shaft torque's following a three-phase fault is computed and analyzed. The obtained results indicate that substantial damping is achieved with a relatively small power rating resistor bank.

List of Symbols

v, i	p.u instantaneous value of voltage and current, respectively
[i]	axis current vector
[v]	machine voltage vector
[L]	inductance matrix
[R]	machine resistance matrix
[G]	rotational voinductance matrix
T_G	electro-magnetic torque in pu.
[J]	moment of inertia matrix
[δ]	load angle vector
[K]	shaft stiffness matrix
[T]	torque vector
[v_{dqo}]	dqo reference frame voltage vector
ω_b	system frequency, rad/s
ω_g	angular velocity of the generator rotor
ω_h	angular velocity of the high pressure turbine

v_c capacitor voltage
p derivative operator d/dt
s laplace operator
α firing angle

Subscripts

d,q direct and quadrature axis
c capacitor
fd direct axis field
kq1 1st quadrature axis damper
kq2 2nd quadrature axis damper
kd dicct axis damper
m maximum
G generator
H high pressure turbine
E exciter
L low pressure turbine

Superscripts

m machine
xc capacitor

Introduction

The adequate operation of power systems requires a transfer of larger blocks of power over longer distances. One of the most economical methods usually used to increase the power transfer capability of EHV transmission lines is the insertion of series capacitors. The presence of series capacitors has given rise to the phenomenon of Sub-synchronous Resonance (SSR). As a result of switching or other disturbances in the series compensated power system, the turbine generator (T-G) set experiences torsional oscillations in the sub-synchronous frequency range (2-45 Hz). The main concern with the torsional oscillations of a T-G set is the possibility of shaft damage as a result of torsional stresses. Review of the literature reveals that many countermeasures to this phenomenon have been reported [1-3]. However, there has been no general solution for the torsional problem and in each system the countermeasure should be selected and designed based on the system characteristics.

Dynamic braking resistors can be applied to power plants or power pools where there is a temporary and large surplus of electric power due to a serious system fault that causes the system to loose its stability quickly. The first development of dynamic braking resistors was performed by B.C. Hydro [4]. An 1400 MW dynamic braking resistor bank was also applied to a temporarily surplus electric power pool at the Northwest power pool and the Southwest power pool of the WSCC (Western Systems Coordinating

Council) [5]. The purpose of using dynamic resistor banks was at that time, primarily for enhancing system transient stability following major system disturbances [5-7]. However, damping of torsional oscillations using a dynamically controlled resistor bank has not been reported until 1981.

Reference [8] suggested using a small dynamic braking resistor of about 6% of the generator rating. The generator speed signal is used as a feedback signal after filtering out the low frequency components and taking the torsional components only to activate the thyristor. The resistor bank is in service only whenever the torsional components of the generator speed signal exceed a preset value. Although the simulation results in [8] showed an increase in the system damping to the torsional oscillatory modes, the design of the controller did not rely on a systematic approach and the parameters were arbitrarily selected. In [9], a unified approach is used to design a (PID) controller but the permanent existence of the braking resistor will reduce the system efficiency. The dynamic model of the thyristor controlled braking resistor in [8,9] is not complete.

In this paper, a method for damping the inertial and all torsional oscillatory modes of the T-G sets using TCBR is presented. Following a major system disturbance, the power consumed by the TCBR is controlled to damp the inertial and the torsional oscillations of the T-G set. During normal operation, a small TCBR module can be left in service to protect the system against small perturbations. In this study a complete dynamic model, utilizing the generator and the high-pressure turbine speed deviations as feedback signals, for the system and TCBR is developed. The pole placement technique is used to determine the control system parameters. The effectiveness of the proposed method on the system performance when subjected to a large disturbance is demonstrated. System-I of the second IEEE benchmark for the simulation of the sub-synchronous oscillation [10] is used in the study.

System under Study

The system under study consists of a 600 MVA steam T-G set connected to an infinite bus as shown in Fig.1. A thyristor controlled resistor bank (TCRB) is connected at the generator bus. The IEEE Type-1 excitation system [11] is used in the studies. The shaft system of the T-G set comprises four masses: one high-pressure turbine (HP), one low-pressure turbine (LP), generator rotor (G), and exciter (EXC). The shaft system has three torsional modes at frequencies 24.65 Hz, 32.39 Hz and 51.10 Hz. The first and second torsional modes experience instabilities due to series compensation. The third torsional mode is marginally stable. The system electro-mechanical data is provided in [10].

Mathematical Model

A- Synchronous machine

Subject to the assumptions pertaining to the two-axis theory [12], the current state space model of a synchronous generator in the rotor reference frame takes the following form:

$$p[i] = [L]^{-1}\{[u] - ([R] + \omega_g [G])[i]\} \tag{1}$$

The vector of the two axis winding currents is given by:

$$[i] = [i_d, i_{fd}, i_q, i_{kq1}, i_{kd}, i_{kq2}]^T$$

and that of voltages by:

$$[u] = [v_d^m, v_{fd}, v_q^m, 0,0,0]^T$$

[L], [R], [G] are given in [13].

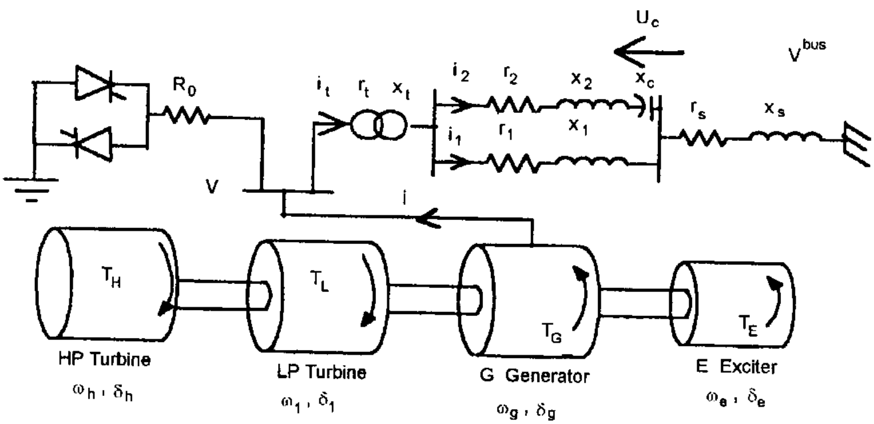

Fig. 1. System under study.

The above model contains one damper circuit on the d-axis and two damper circuits on the q-axis in order to represent the effects of the damper windings in the generator. The axes currents from Eqn.1 are used to calculate the electrical torque, T_G, as follows:

$$T_G = -[i]^T [G][i]\omega_g \tag{2}$$

B- Mechanical system

The mechanical system is represented in Fig.1 as four inertias interconnected by three torsional springs (the connecting shafts), and can be described by:

$$[J]p^2[\delta]+[D]p[\delta]+[K][\delta]+[T]=0 \tag{3}$$

where [J] is a diagonal matrix of inertias, [D] is a diagonal matrix of damping coefficients, [K] is a symmetric matrix of shaft stiffnesses, [T] is a forcing torque vector and [δ] is an angular position vector.

C- Excitation system

Type-1 IEEE excitation system shown in Fig. 2 is considered. The state space representation of such a high-speed excitation system is given by:

$$[pX_e]=[A_e][X_e]+[B_e][U_e] \tag{4}$$

where:

$$[X_e]=[v_a, v_{fd}, v_b]^T$$

$$[U_e]=[V_{ref}, V^m]^T$$

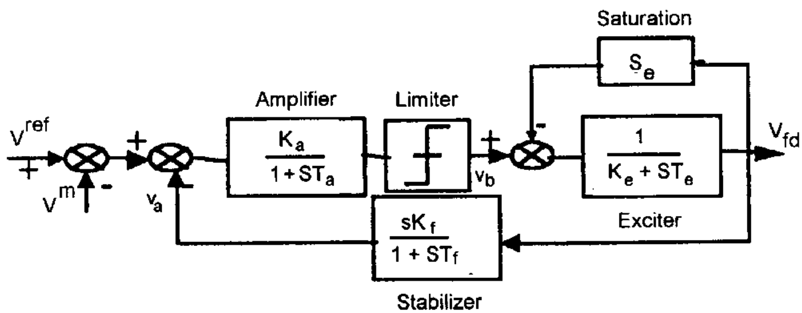

Fig. 2 Excitation system.

[Ae] and [Be] are the state and control matrices of the excitation system and can be derived directly from the block diagram.

D- Transmission system

The two-axis voltage vector at the machine terminals in Fig.1 is given by:

$$[v^m_{dqo}]=[v^{bus}_{dqo}]-[v^{z_t}_{dqo}]-[v^{z_l}_{dqo}]-[v^{z_s}_{dqo}] \tag{5}$$

where the terms on the right-hand side of Equation 5 are the infinite bus voltage, the volt drops across the series impedance z_t, the first transmission line impedance z_l, and the series impedance z_s.

The d-q axis voltage components for any inductive impedance z_x can be obtained from:

$$v_d^{z_x} = r_x i_{xd} + x_x p i_{xd} + \omega_g x_x i_{xq}$$

$$v_q^{z_x} = r_x i_{xq} + x_x p i_{xq} - \omega_g x_x i_{xd}$$

Applying Kirchhoff's voltage law along the two parallel transmissions lines yields:

$$[v_{dqo}^{z_1}] = [v_{dqo}^{z_2}] + [v_{dqo}^{x_c}] \tag{6}$$

where:

$$p v_d^{x_c} = x_c i_{2d} + \omega_g v_q^{x_c}$$

$$p v_q^{x_c} = x_c i_{2q} - \omega_g v_d^{x_c}$$

E- Thyristor controlled braking resistor

In this study, the resistors and the firing angle are chosen so that with rated voltage applied, the resistor bank is capable of dissipating 6% of the generator rated power. The applied voltage and the current flowing through the resistor R_o are shown in Fig.3a and given by:

$$v = V_m \sin \omega_o t \tag{7}$$

$$i_b = \begin{bmatrix} \frac{V_m}{R_o} \sin \omega_o t & \alpha \le \omega_o t \le \pi \\ \frac{V_m}{R_o} \sin \omega_o t & \pi + \alpha \le \omega_o t \le 2\pi \\ 0 & \text{elsewhere} \end{bmatrix} \tag{8}$$

The fundamental current obtained from analyzing the current waveform by Fourier analysis consists of two components; one in phase with the voltage; the other component lags the voltage wave by 90 degrees. The fundamental current waveform is given by:

$$i = I_{m1} \sin \omega_0 t + I_{m2} \cos \omega_0 t \tag{9}$$

where:

$$I_{m1} = V_m (1 - C_o) / R_o$$

$$I_{m2} = V_m (C_1 - 1) / R_o$$

$$C_o = (\alpha\pi - \sin(2\alpha)) / (2\pi)$$

$$C_1 = \cos(2\alpha)$$

The TCBR can be considered as a variable inductive load. This load consists of two parallel branches as shown in Fig.3b. The branch, which represents the active power drawn from the system, is modeled by an inertialess voltage source of magnitude $(C_o V)$ behind a resistor R_o. Another inertialess voltage source of magnitude $(C_1 V)$ behind an equivalent inductive reactance X_{eq} models the reactive power branch.

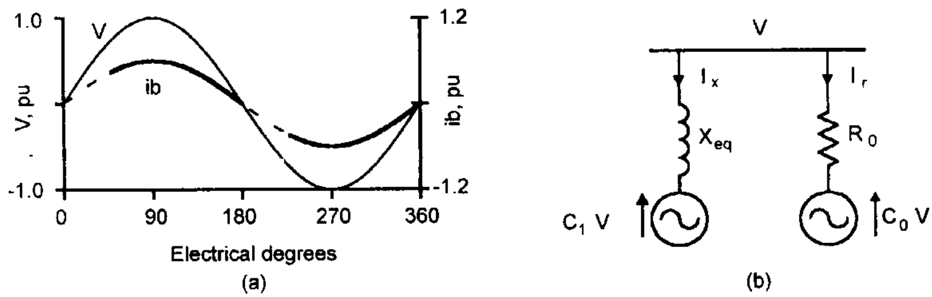

Fig. 3a. Voltage and current wave form, b. TCBR equivalent.

Figure 4.a shows the variation of the in phase current component (I_r), and the reactive current component (I_x), as a function of the firing angle alpha. The variations in the active and reactive power taken from the system are shown in Fig.4b. The rate of change of the active and reactive power is shown in Fig.4c.

The d-q model of the TCBR is given by:

$$(i_{dr} + j i_{qr}) = (1 - C_o)(v_d^m + j v_q^m) / R_o \tag{10}$$

and

$$(1 - C_1)(v_d^m + j v_q^m) = \frac{x_{eq}}{\omega_o}[(-\omega_g i_{xq} + p i_{xd}) + j(\omega_g i_{xd} + p i_{xq})] \tag{11}$$

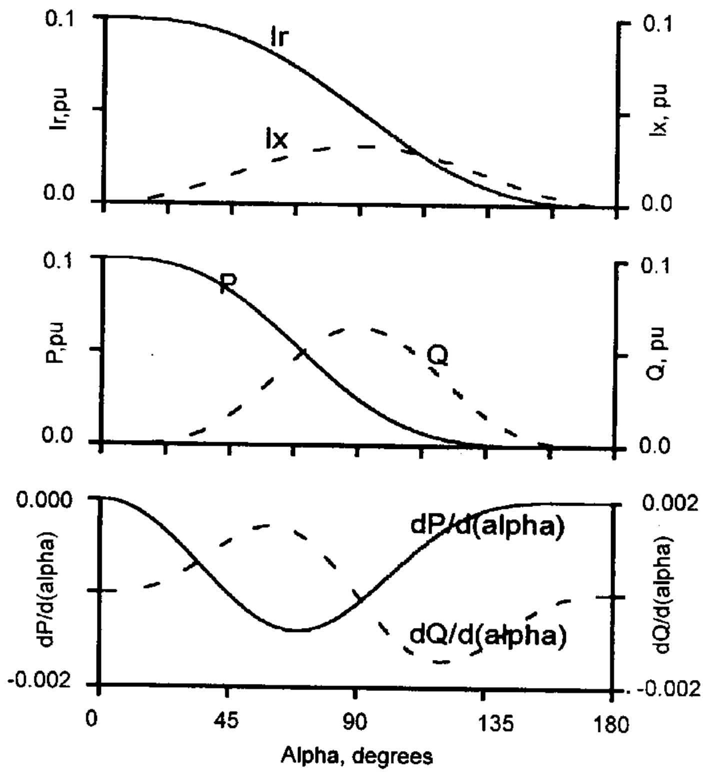

Fig. 4 (a). Variations in the TCBR currents, (b) Variations in active and reactive power, (c) Rate of change of active and reactive power.

IV- Design of the TCRB control system

Figure 5 shows the block diagram of the resistor bank control system. The generator and the high-pressure speed deviations are used as feedback signals. The output from the control system is used to modify the firing angle of the thyristor and consequently modulating the active and reactive power at the generator bus. The nonlinear system equations 1-11 of the system are linearized around a nominal operating condition. The pole placement method is then applied to determine a proper set of controller parameters. The linearized state equation of the power system is written in the vector matrix differential form:

$$[s\Delta X(s)] = [A][\Delta X(s)] + [B][\Delta U(s)] \tag{12}$$

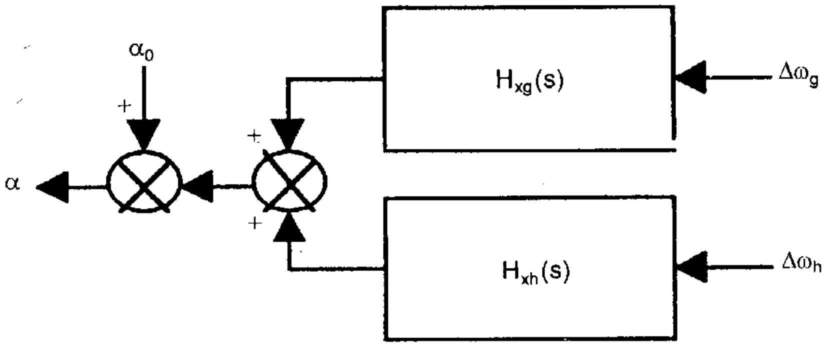

Fig. 5. Block diagram of the control system.

Equation (12) can be re-written in the following form:

$$\begin{bmatrix} s\Delta X_1 \\ s\Delta X_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} \Delta X_1 \\ \Delta X_2 \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} [\Delta U] \tag{13}$$

where:

$$[\Delta X_1] = [\text{all states without } \omega_g \text{ and } \Delta\omega_h]^T$$

$$[\Delta X_2] = [\Delta\omega_g, \Delta\omega_h]^T$$

$$[\Delta U] = [H_{xg} \quad H_{xh}][Y] \tag{14}$$

where:

$$H_{xg} = \frac{T_{w1}s}{1+T_{w1}s}\left[K_{P1} + \frac{K_{I1}}{s} + K_{D1}s\right]$$

$$H_{xh} = \frac{T_{w2}s}{1+T_{w2}s}\left[K_{P2} + \frac{K_{I2}}{s} + K_{D2}s\right]$$

Y(s) is the input vector to the controller and given by:

$$[Y(s)] = [C][\Delta X_2(s)] \tag{15}$$

$$[B_2]=0 \tag{16}$$

From equations13-16

$$Det[sI- A_{22} -A_{21} (sI-A_{11})^{-1}(A_{12}+B_1H_x(s)C]=0 \quad (17)$$

The washout time constants T_{w1} and T_{w2} are assumed. A location λ_x for an oscillatory mode is specified. Replacing s by λ_x in Eqn. 17 yields two real equations. Since three oscillatory modes will be specified, there will be six real equations in six unknowns. The control system parameters are obtained from these equations. In this study the specified locations for the inertial, first, and second torsional modes are:

$$\lambda_0 = -1.5 \pm j\ 10.2$$

$$\lambda_1 = -2.5 \pm j\ 154.3$$

$$\lambda_2 = -3.0 \pm j\ 203.7$$

The obtained parameters for the TCBR control system are:

K_{P1}=-0.486 K_{I1}=425.92 K_{D1}=0.00429

K_{P2}=-0.102 K_{I2}=-421.9 K_{D2}=-0.0196

Study Results

A- Eigenvalue analysis

An eigenvalue analysis is performed on the system under study to investigate the effect of the TCBR on the decrement factor of the inertial and torsional modes. The eigenvalues of the system without controllers are summarized in the first column of Table 1. The numerical values for Table 1 is obtained when the generator delivers 100% of its rated MVA at 0.90 lagging power factor and the compensation level is 52%. It is obvious that the first torsional mode is negatively damped while the other torsional modes are marginally stable. The effect of applying the stabilizing signal is shown in the second column of Table 1. The results indicate that, the inertial, the first and the second torsional modes stability are enhanced and their corresponding roots are located at the prespecified location. Moreover, the control system has no effect on the other system roots.

Table 1. Inertial and torsional modes with and without TCBR

	Without TCBR	With TCBR
Mode 3	-0.040 ± j321.26	-0.025 ± j321.80
Mode 2	-0.260 ± j203.63	-3.000 ± j203.69
Mode 1	+0.320 ±155.38	-2.499 ± j154.30
Inertial Mode	-0.440 ±j 9.51	-1.500 ± j10.193

In order to check the robustness of the proposed controller under different values of compensation level, the decrement factor of the inertial, first and second torsional modes are obtained and plotted in Fig. 6. This figure reveals that as a result of active and reactive power modulation at the generator bus, the electrical system damping to the inertial, first, and second torsional modes is increased in the whole range of series compensation.

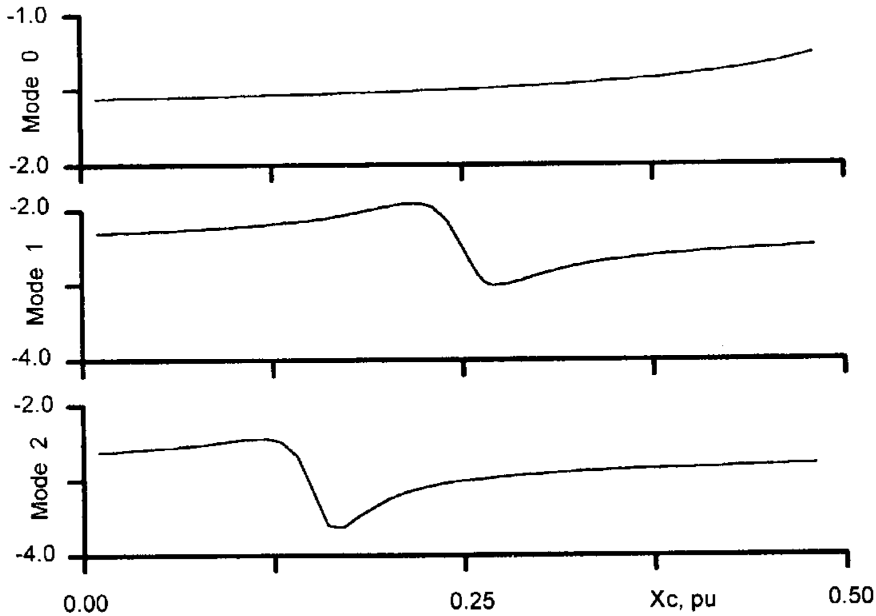

Fig. 6. Decrement factors of the inertial, first, and second torsional modes.

B- Digital computer simulation

To demonstrate the effectiveness of the proposed TCBR and the designed PID controllers, which has been designed based on a linearized system model, time domain approach based on a nonlinear system model is carried out in this section. All system nonlinearities such as exciter ceilings, upper and lower limits of the firing angle are included. Fig.7 shows the transient response of the system when subjected to a severe three-phase fault, which starts at 0.1 second and lasts for three cycles of 60 Hz base at infinite bus. It is clear that the system experience instability and the torsional stresses on the generator shaft segments are very severe. Fig.8 shows the system response when the proposed TCBR and its control system are in service. The results indicate that substantial damping is achieved with the proposed method.

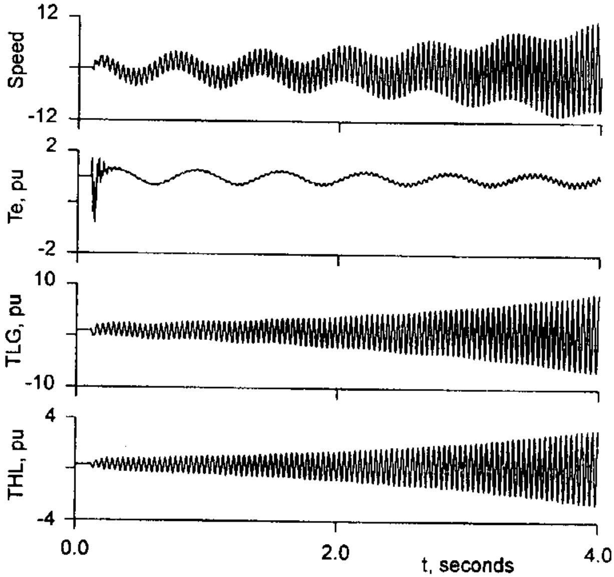

Fig. 7 System response following 3-phase short circuit without TCBR.
Note : Speed means generator speed deviation in rad/sec.

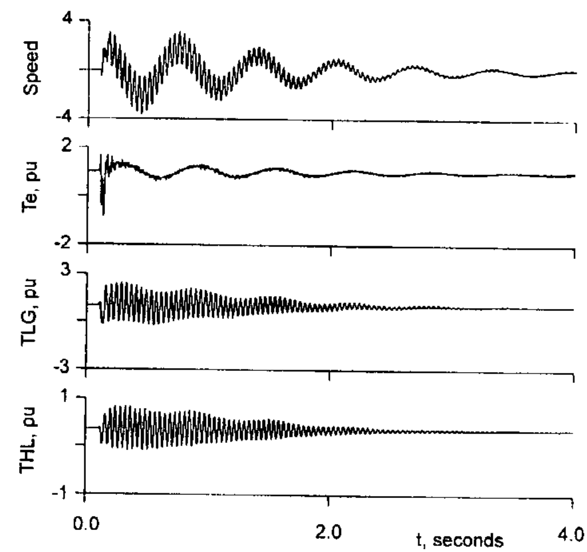

Fig. 8 System response following 3 phase short circuit with TCBR in service
Note : Speed means generator speed deviation in rad/sec.

Conclusion

The technical feasibility of using a thyristor controlled braking resistor to damp shaft oscillations in large steam turbo-generator has been investigated. A complete dynamic model, utilizing the generator and the high-pressure turbine speed deviations as feedback signals, for the system and TCBR is developed. The power consumed by the resistor is controlled to increase the system damping to the inertial and torsional oscillatory modes following serious system disturbances. During normal operation, a small TCBR module can be left in service to protect the system against small perturbations. The investigations indicate that substantial damping is achieved over a wide range of series compensation for the inertial, first and second torsional modes. The effect of the proposed method on the third torsional mode is insignificant. The stability of this mode can be enhanced if needed by adding one channel on the control system and using either the generator power angle or any other measurable signal as a feedback.

References

[1] IEEE SSR Working Group. "Countermeasures to Subsynchronous Resonance Problems." *IEEE Trans. PAS.*, 99 (1980), 1812-1818.

[2] Chi-Juiwu and Chun-Fengiu. "Damping Torsional Oscillations by a Super-conducting Magnetic Energy Storage Unit." *Electric Machines and Power Systems*, 22, No.1 (Jan-Feb. 1994), 1-15.

[3] Abdennour, Adel Ben, Hamouda, Rizk M. and Al-Ohaly, A.A. "Countermeasures for Self-excited Torsional Oscillations Using Reduced Order Robust Control Approach." *Paper # PE-179PRS (11-99) recommended and approved by the IEEE Power System Performance Committee of the IEEE Power Engineering Society for publication in the IEEE Transactions on Power Systems*, 1999.

[4] Ellis, H.M., Hardy, J.E., Blythe, A.L. and Skooglund, J.W. "Dynamic Stability of the Peace River Transmission System." *IEEE Trans. PAS.*, 85 (1966), 586-600.

[5] "Power Administration 1400-MW Braking Resistor." *IEEE Trans., PAS.*, M.L. Shelton, W.A. Mittelstadt, P.F. Winkelman, and W.J. Bellerby, *Bonneville,* 94 (1975), 602-611.

[6] Yoshida, K., Fukunishi, M. and Aol., J. "Development of System-damping Resistors for Stabilizing Bulk Power Transmission." *Electrical Engineering in Japan*, 91, No.3 (1971), 79-90.

[7] Miniesy, S.M. and E.V. Bohm. "Optimal Network Switching in Power Systems." *IEEE Trans. PAS.*, 90 (1971), 2118-2122.

[8] O. Wasyncsuk, "Damping Shaft Torsional Oscillations Using Dynamically Controlled Resistor Bank." *IEEE Trans. PAS.*, 100 (1981), 3340-3349.

[9] Wang, Li and Ching-Huei. Lee. "Application of Dynamic Resistance Braking on Stabilizing Torsional Oscillations." *Proceeding of the 1993 IEEE Region 10 Conference on Computer, Communication, Control and Power Engineering*, Beijing, (1993), 145-148.

[10] IEEE SSR Working Group, "Second Benchmark Model for Computer Simulation of Subsynchronous Resonance." *IEEE Trans. PAS.*, 104 (1985), 1057-1066.

[11] IEEE Committee Report "Computer Representation of Excitation Systems." *IEEE Trans.*, PAS-87 (1968), 1460-1464.

[12] Adkins, B. and Harley, R.G. *The General Theory of Alternating Current Machines. Applications to Practical Problems*, Chapman and Hall, 1975.

[13] Limebeer, D.J.N, Harley, R.G. and Schunk, S.M. "Sub-synchronous Resonance of the Koeberg Turbo-Generator and of a Laboratory Systems." *IEE Trans.*, (South Africa), 70 (1979), P(11), 278-297.

إخماد الاهتزازات الالتوائية باستخدام مقاومات كوابح تحت تحكم الثايرستور

رزق محمد السيد حمودة

قسم الهندسة الكهربائية ، كلية الهندسة ، جامعة الملك سعود ، ص ب ٨٠٠،
الرياض ١١٤٢١ ، المملكة العربية السعودية

(قدم للنشر في ١٩/١٠/١٩٩٩ ، وقبل للنشر في ٠٤/٠٤/٢٠٠٠)

ملخص البحث. قدّم هذا البحث طريقة جديدة للتحكم في مقاومة كوابح ديناميكية بنظام القدرة تسمح لمقاومة الكوابح التي يتحكم بها ثايرستور بإخماد فعّال لاهتزازات القصور الذاتي والالتوائي في مولد كبير . تم عمل الدراسة على النظام الأول في نموذج IEEE الثاني لمحاكاة ذبذبات دون التزامن باستخدام طريقة الأحادية وتم التحقق بمحاكاة رقمية تفصيلية . تم عمل نموذج ديناميكي لمقاومات الكوابح . استخدمت طريقة وضع الجذور لتصميم نظام التحكم في زاوية الإشعال وتم حساب عزم العمود وتحليله في حالة حدوث قصور ثلاثي الطور . تبين النتائج التي تم الحصول عليها أن إخمادا كبيرا قد تحقق باستخدام مقاومات ذات قدرة صغيرة .