

DAMPING OF SUBSYNCHRONOUS RESONANCE OSCILLATIONS USING THE VOLTAGE MAGNITUDE AND PHASE ANGLE CONTROL OF STATIC PHASE SHIFTER

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ABSTRACT– The voltage magnitude and phase Angle control of static phase shifter (VMPA–SPS) to damp the subsynchronous resonance(SSR) oscillations is investigated. A linear mathematical model of series-compensated transmission line power system with static phase shifter is developed .The input control signals to the simulated power system is the phase angle and voltage magnitude deviations of static phase shifter. A controllability measure based on singular value decomposition (SVD) is used to identify the effectiveness of each control input signal on the electromechanical modes. A state feedback supplementary controller based on the linear quadratic regulator principle with a full rank observer is used to modulate the voltage magnitude and phase angle deviations of SPS to stabilize the SSR modes under different operating conditions and compensation levels of the compensated transmission line. To validate the effectiveness of the proposed supplementary controller , the studied power system is subjected to different disturbances. The digital simulation results prove the powerful of the proposed static phase shifter supplementary controller in terms of the fast damping of the SSR oscillations with less overshoot/undershoot.

I- INTRODUCTION

Fixed Capacitors have long been used to increase the steady state power transfer capabilities of transmission lines. A major concern associated with fixed series capacitors is the subsynchronous resonance (SSR) phenomenon which arise as a result oh the interaction between the compensated transmission line and turbine generator shaft. This results in excessively high oscillatory torque on machine shafts causing their fatigue and damage. The first two shaft failures due to SSR occurred at the Mohave station in 1970 and 1971[1], [2] since that numerous countermeasures have been used to damp SSR such as blocking filters, excitation controllers, dynamic filters, thyristor-controlled series compensator (TCSC), static phase shifter (SPS), and many other flexible AC transmission systems (FACTS) devices[3-14]. Considerable studies have been conducted in using phase angle control of SPS(PA-SPS) to damp out SSR modes oscillations [15], [16]. While the voltage magnitude and phase angle control

$$\begin{aligned}
 X = & [\Delta W_H, \Delta\theta_H, \Delta W_I, \Delta\theta_I, \Delta W_A, \Delta\theta_A, \Delta W_B, \\
 & \Delta\theta_B, \Delta W, \Delta\theta, \Delta W_X, \Delta\theta_X, \Delta a, \Delta g, \Delta T_H, \Delta T_I, \\
 & \Delta T_A, \Delta e_{cd}, \Delta e_{cq}, \Delta I_d, \Delta I_q, \Delta I_f, \Delta I_D, \Delta I_Q, \\
 & \Delta I_s, \Delta V_R, \Delta E_{fd}]^T
 \end{aligned}
 \tag{3}$$

While A , B, and C are constant matrix and vectors depend upon the power system parameters and operating conditions.

2.2- Static Phase Shifter Model

The static phase shifter SPS comprises a magnetizing transformer T_1 connected in shunt, series transformer T_2 and a switching network (converters) as shown in **Fig. 2**. the magnitude and phase shift are obtained by extracting the line-to-ground voltage of one phase and injecting a portion of it -which is selected by the switching network- in series with another phase. Therefore the voltage magnitude and phase shift control can be obtained. To develop SPS Model the following simplified figures is considered [14].

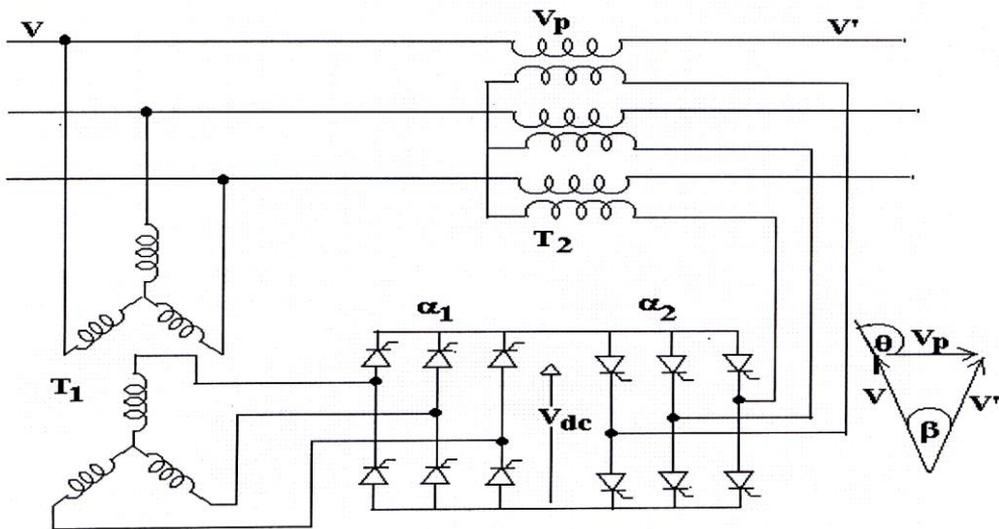


Fig. 2: A phase shifter configuration.

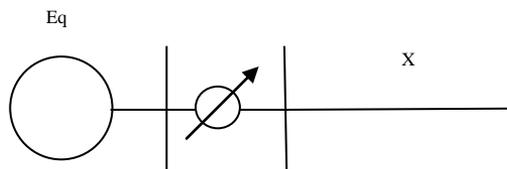


Fig. 3a: simplified system diagram.

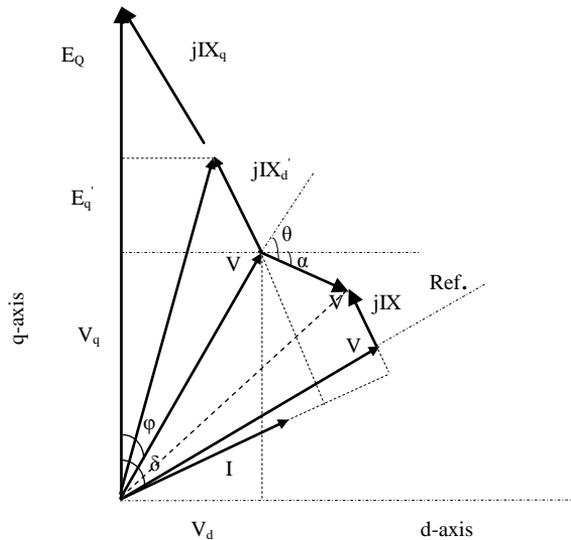


Fig 3.b: Phasor diagram of the system.

Terminal voltage in terms of direct and quadrature components is given by:

$$V_t^2 = V_d^2 + V_q^2 \quad (4)$$

From the geometry of the phasor diagram shown in Fig. (3.b) the following equations are obtained ,

$$V_d = RI_d - XI_q + (X / \omega b) \dot{I}_d + e_{cd} + V_o \sin \delta - V_p \cos \alpha \quad (5)$$

$$V_q = XI_d + RI_q + (X / \omega b) \dot{I}_q + e_{cq} + V_o \cos \delta - V_p \sin \alpha \quad (6)$$

$$\alpha = \theta_p + \phi - \frac{\pi}{2} \quad (7)$$

$$\sin \phi = V_d / V_t \quad (8)$$

The above non-linear equations are linearized and the results are:

$$\Delta V_t = (V_{d_o} / V_{t_o}) \Delta V_d + (V_{q_o} / V_{t_o}) \Delta V_q \quad (9)$$

$$(10) \quad \Delta V_d = R \Delta I_d - X \Delta I_q + (X / \omega b) \Delta \dot{I}_d + \Delta e_{cd} + (V_o \cos \delta_o) \Delta \delta + (V_{p_o} \sin \alpha_o) \Delta \alpha - (\cos \alpha_o) \Delta V_p$$

$$\Delta V_q = X \Delta I_d + R \Delta I_q + (X / \omega b) \Delta \dot{I}_q + \Delta e_{cq} - (V_o \sin \delta_o) \Delta \delta - (V_{p_o} \cos \alpha_o) \Delta \alpha - (\sin \alpha_o) \Delta V_p \quad (11)$$

$$\Delta \alpha = \Delta \theta_p + \Delta \phi \quad (12)$$

$$\Delta\alpha = \Delta\theta_p + (V_{t\circ}\Delta V_d - V_{d\circ}\Delta V_t)/(V_{q\circ}V_{t\circ}) \tag{13}$$

by substituting $\Delta\alpha$ from Eq. (13) in Eqs. (10),(11) making some algebraic manipulation yields :

$$\begin{aligned} \Delta V_d = & M_\delta\Delta\delta + M_\omega\Delta\omega + M_d\Delta I_d + M_q\Delta I_q + M_{cd}\Delta e_{cd} \\ & + M_{cq}\Delta e_{cq} + M_f\Delta I_f + M_D\Delta I_D + M_Q\Delta I_Q + M_s\Delta I_s \\ & + M_{fd}\Delta E_{fd} + M_\theta\Delta\theta_p + M_p\Delta V_p \end{aligned} \tag{14}$$

$$\begin{aligned} \Delta V_q = & N_\delta\Delta\delta + N_\omega\Delta\omega + N_d\Delta I_d + N_q\Delta I_q + N_{cd}\Delta e_{cd} \\ & + N_{cq}\Delta e_{cq} + N_f\Delta I_f + N_D\Delta I_D + N_Q\Delta I_Q + N_s\Delta I_s \\ & + N_{fd}\Delta E_{fd} + N_\theta\Delta\theta_p + N_p\Delta V_p \end{aligned} \tag{15}$$

Where M 's and N 's symbols are constants.

ΔV_p is the injected voltage magnitude deviation of SPS

$\Delta\theta_p$ is the injected voltage phase shift deviation of SPS

The operation of Static Phase Shifter circuit shown in **Fig. 2** can be modelled in transfer functions as shown in **Fig. 4**, Where K 's and T 's are the gain and time constant of the phase shifter circuit of $K_{s1}=0.01, K_{s2}=0.1, T_{s1}=T_{s2}=0.05$.

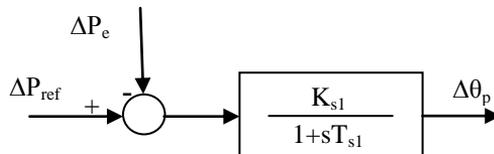


Fig. 4a: Static Phase Shifter Active Power Regulator.

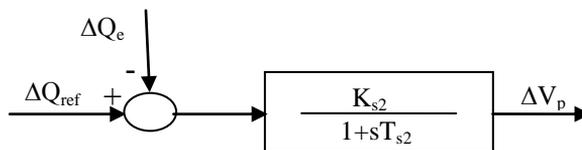


Fig. 4b: Static Phase Shifter Reactive Power Regulator.

2.3 Studied Power System With SPS Modelling

Substituting the linearized equations of SPS defined in eqs.(14,15) in the state space equations of power system with SPS, the dynamic equations of whole system is obtained. To modulate the injected voltage magnitude and phase shift deviations of SPS, the input signals to the transfer function block diagrams of $\Delta\theta$ and ΔV_p of SPS are the differences between the reference and actual values of electrical active and reactive output powers of synchronous generator respectively as shown in **Fig. 4**. The electrical active and reactive output powers of the generator can be expressed by following equations :

$$P_e = V_d I_d + V_q I_q \quad (16)$$

$$Q_e = V_d I_q - V_q I_d \quad (17)$$

The linearized form of the above equations is given by:

$$\Delta P_e = I_{d0} \Delta V_d + V_{d0} \Delta I_d + V_{q0} \Delta I_q + I_{q0} \Delta V_q \quad (18)$$

$$\Delta Q_e = I_{q0} \Delta V_d + V_{d0} \Delta I_q - V_{q0} \Delta I_d - I_{d0} \Delta V_q \quad (19)$$

Incorporating the SPS model ,the State equation of the combined system will be as follows:

$$xM = AM * xM + BM * Ua \quad (20)$$

$$yM = CM * xM \quad (21)$$

where state vector becomes

$$\begin{aligned} XM = & [\Delta W_H, \Delta \theta_H, \Delta W_I, \Delta \theta_I, \Delta W_A, \Delta \theta_A, \Delta W_B, \\ & \Delta \theta_B, \Delta W, \Delta \theta, \Delta W_X, \Delta \theta_X, \Delta a, \Delta g, \Delta T_H, \\ & \Delta T_I, \Delta T_A, \Delta e_{cd}, \Delta e_{cq}, \Delta I_d, \Delta I_q, \Delta I_f, \Delta I_D, \\ & \Delta I_Q, \Delta I_s, \Delta V_R, \Delta E_{fd}, \Delta \theta_p, \Delta V_p]^T \end{aligned} \quad (22)$$

While AM and BM, CM are the constant matrix and vectors of the combined system.

3- PROPOSED SUPPLEMENTARY CONTROLLER DESIGN FOR SPS

In order to damp out the SSR oscillations, the state feedback controller defined by Linear Quadratic Regulator LQR is implemented .The supplementary control signal U_a given in equation (5) is determined by $U_a = -K X$ Where K is feedback gain vector generated from the proposed supplementary controller LQR . There are two control loops for SPS defined by ΔV_p and $\Delta \theta$ loops. To find either effective control loop of SPS where the control signal of the proposed supplementary controller is sent to it in sense that it causes more damping for SSR oscillation, the singular value decomposition SVD technique is applied. SVC is used To measure the controllability of certain mode by a given input [17]. The output of SVD technique is defined by singular value of matrix $[\lambda I - A : b_i]$, where λ is the eigenvalue of A matrix and b_i is the column i of input B matrix corresponding to input i. Minimum value of singular value indicates the capability of the i-th input to control the mode associated with the eigenvalues λ . However, the proposed supplementary controller for SPS requires full states must be measured. Therefore an observer is designed to estimate the states of studied system.

4- FULL ORDER OBSERVER DESIGN

The state feedback supplementary controller used in this study requires all the system states must be measured. But not all the states are measurable so the observer is designed to estimate the immeasurable state variables. The full order observer to be

described here estimates all the state variables of the system. **Figure 5** shows the system-observer arrangement. From this figure the state equations of the system states (\dot{X}) and the estimated states (\hat{X}) will be as follows :

$$\dot{x} = Ax - BK\hat{x}$$

$$\dot{\hat{x}} = LCx + (A - Bk - LC)\hat{x}$$

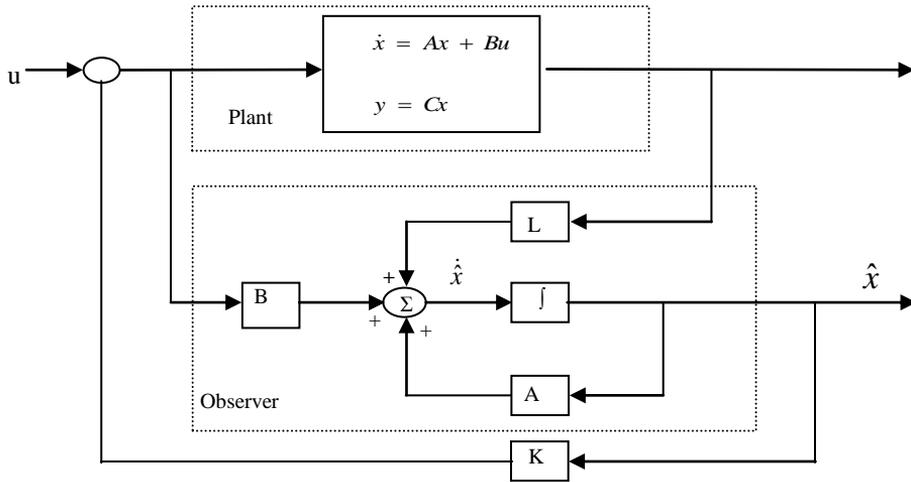


Fig. 5: Full-order observer in a state variable feedback scheme.

5- DIGITAL SIMULATION RESULTS

The data of the power system under study is found in ref[2]. **Figure 6** depicts the minimum singular values with control signal sent to the ΔV_p and $\Delta\theta$ using the eigenvalues of unstable mechanical modes of SSR oscillations under different operating conditions. It is found that when the control signal is sent to both ΔV_p and $\Delta\theta$ loops simultaneously, the damping of SSR oscillations is high and quickly. Therefore the same control signal generated from the supplementary controller is added to generator active power deviation via $\Delta\theta$ loop and is added to reactive power deviation of synchronous generator through ΔV_p loop as shown in **Fig. 7**. To study the effectiveness of the proposed supplementary controller for SPS, the studied power system is subjected to different disturbances such as different operating conditions and series compensation levels (X_c/X_L). **Table 1** shows the eigenvalues of simulated power system without SPS, with SPS and without proposed supplementary controller, and the last column contains the eigenvalue of power system with SPS controlled by the proposed supplementary controller. It is noticed that the proposed supplementary controller causes all eigenvalues of the simulated power system to be stable. The dynamic equations of combined system under study is solved using Fourth order Ruge Kutta modified by Gill in MATALB Software package programs. The power system responses when the system is disturbed by applying the mechanical input signal ΔT_m of value 0.02 per unit are depicted in **Figs. 8-1 : 8-8**.

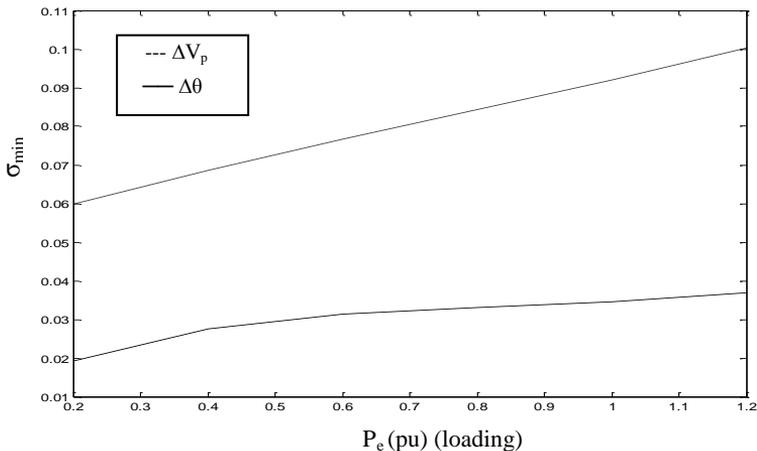


Fig. 6: Minimum singular value decomposition SVD.

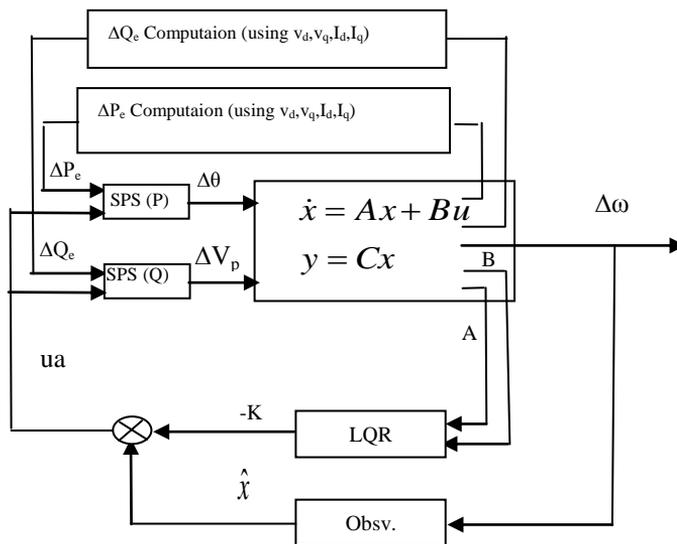


Fig. 7: Studied power system with proposed controller in block diagram.

Table 1: Studied System eigenvalues (rad/sec).

		Without VMPA-SPS	With VMPA-SPS but without controller	With VMPA-SPS and controller
mechanical modes	(5) λ_{HP}	$-0.18 \pm j298.18$	$-0.18 \pm j298.18$	$-0.18 \pm j298.18$
	(4) λ_{IP}	$0.17 \pm j202.63$	$0.02 \pm j202.56$	$-8.78 \pm j205.63$
	(3) λ_{LPA}	$1.15 \pm j161.48$	$1.64 \pm j160.82$	$-11.43 \pm j164.56$
	(2) λ_{EXC}	$-0.68 \pm j127.11$	$-0.64 \pm j127.11$	$-1.21 \pm j125.2$
	(1) λ_{LPB}	$-0.35 \pm j99.68$	$-0.10 \pm j99.72$	$-19.14 \pm j93.02$
	(0) λ_{GEN}	$-0.44 \pm j10.7$	$-0.35 \pm j10.45$	$-19.56 \pm j16.78$

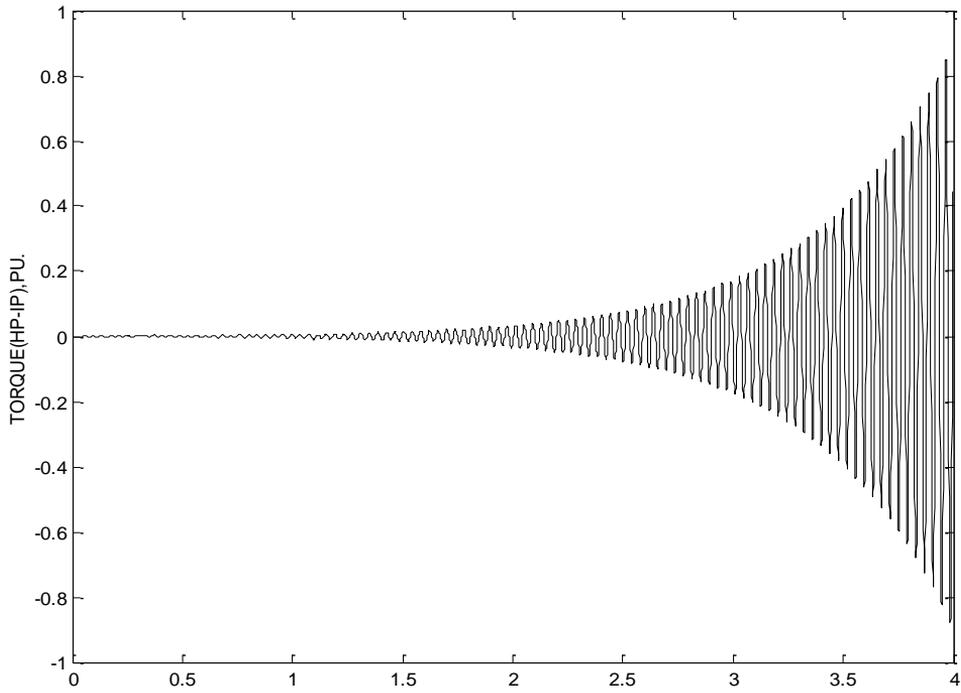


Fig. 8-1: Dynamic response of the studied system with VMPA-SRS without controller.

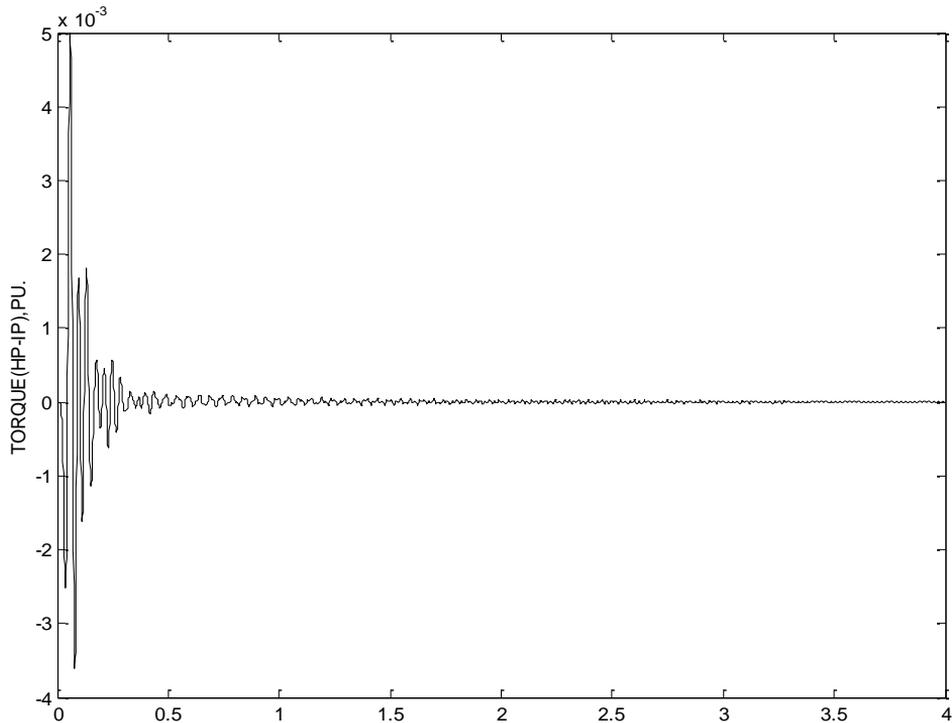
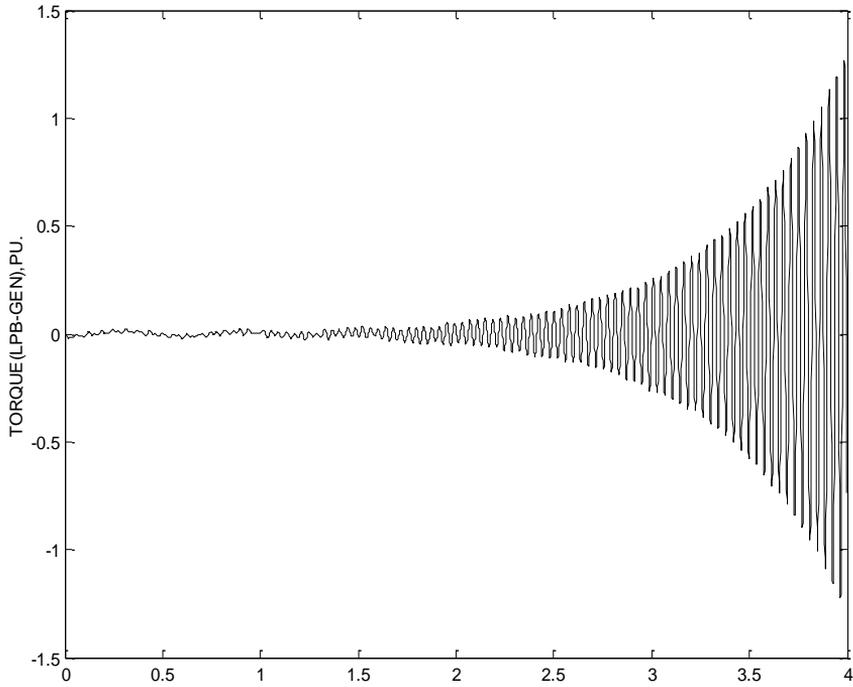


Fig. 8-2: Dynamic response of the studied system with VMPA-SRS with controller.**Fig. 8-3:** Dynamic response of the studied system with VMPA-SRS without controller.

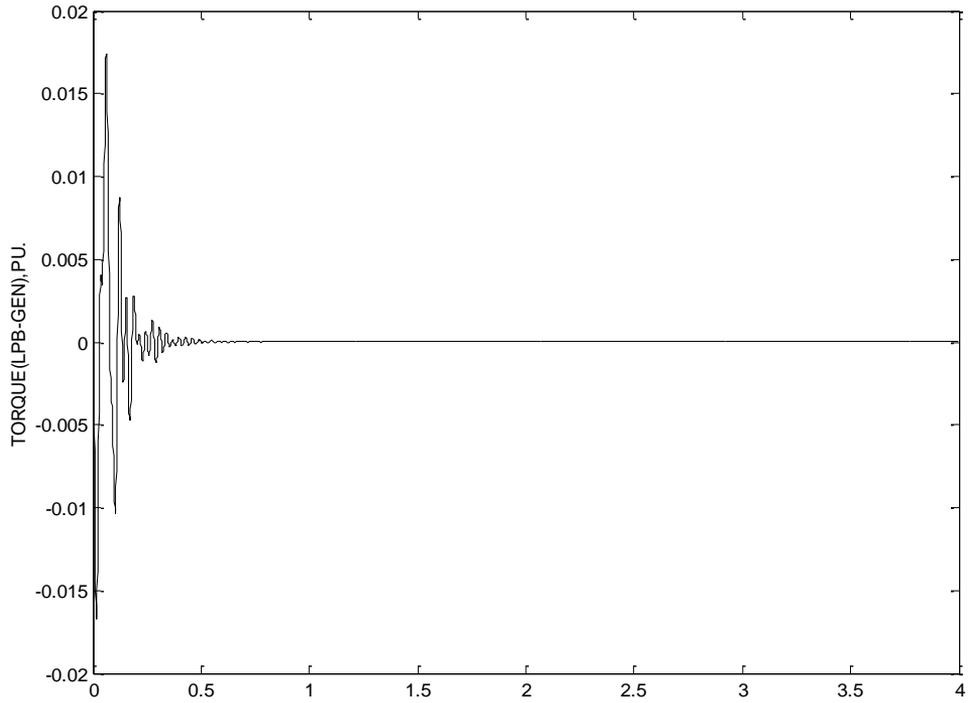


Fig. 8-4: Dynamic response of the studied system with VMPA-SRS with controller.

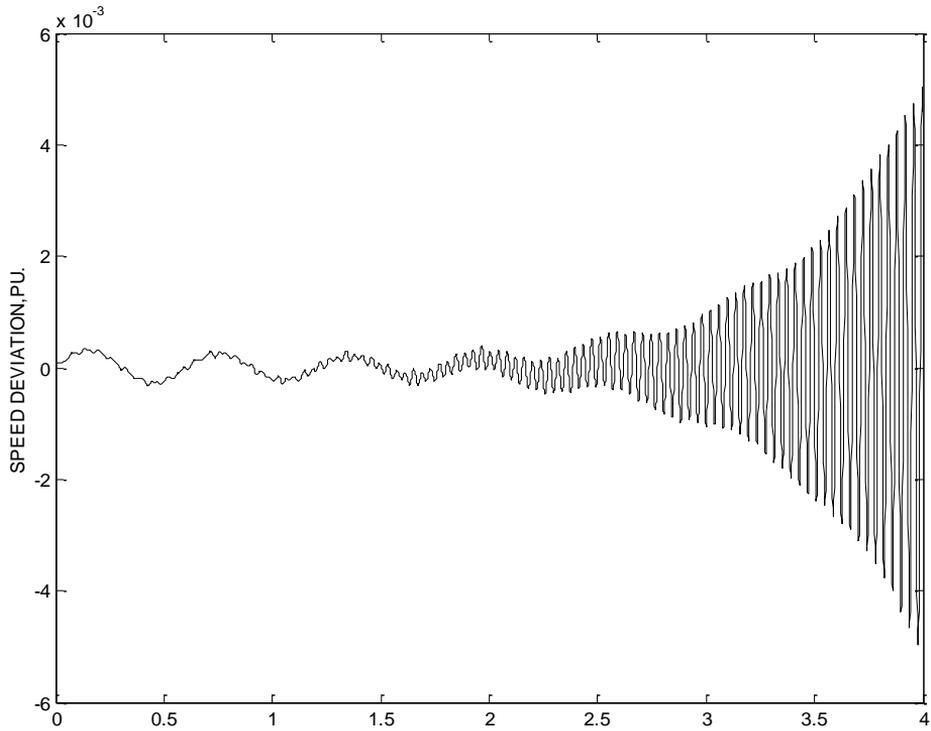


Fig. 8-5: Dynamic response of the studied system with VMPA-SRS without controller.

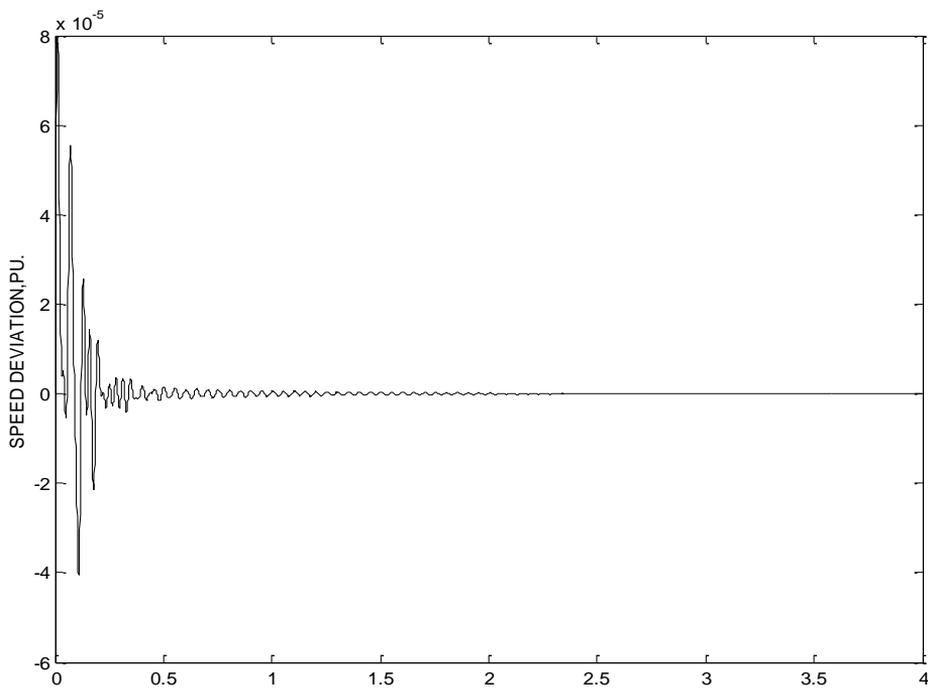


Fig. 8-6: Dynamic response of the studied system with VMPA-SRS with controller.

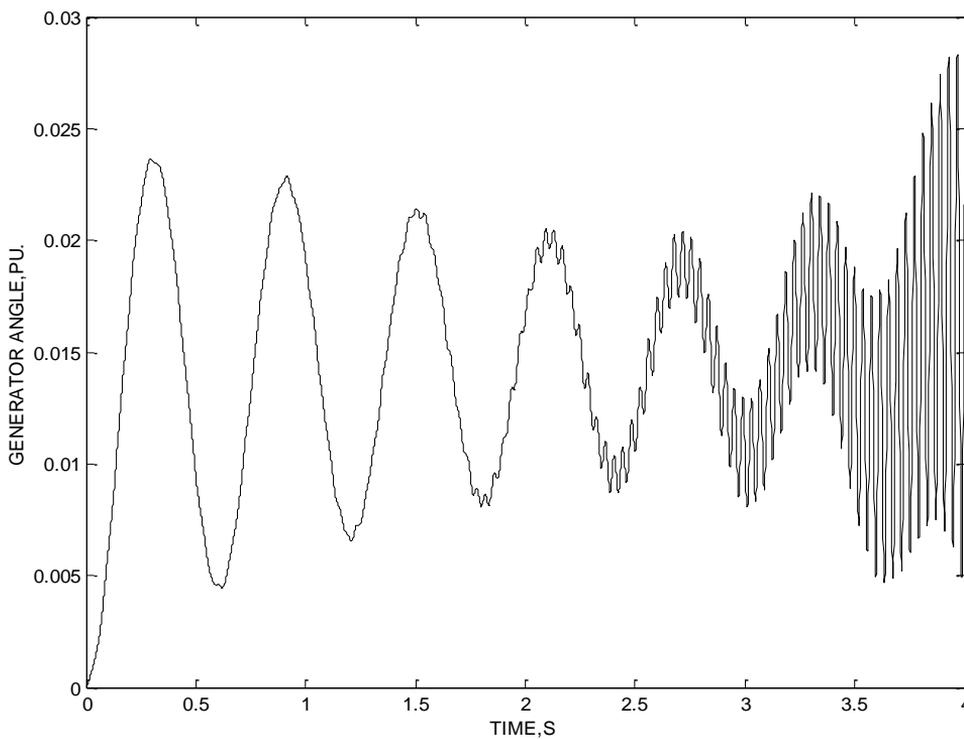
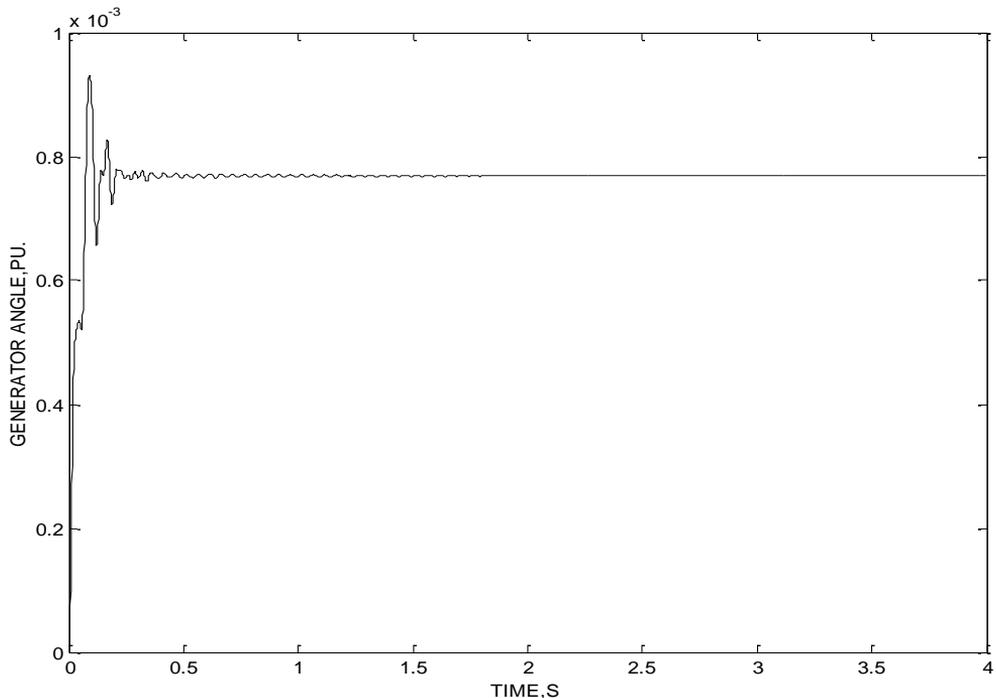


Fig. 8-7: Dynamic response of the studied system with VMPA-SRS without controller.**Fig. 8-8:** Dynamic response of the studied system with VMPA-SRS with controller.

6- CONCLUSIONS

The present paper introduces an application of static phase shifter for damping SSR oscillations. Both the voltage magnitude and phase angle of static phase shifter are controlled simultaneously. A singular value decomposition approach is utilized to measure the capability of the certain input to control the mode associated with the selected eigenvalues. It is found that if the same control signal is sent to modulate both the voltage magnitude and the phase angle of phase shifter, the SSR Oscillations damping is quickly. A supplementary controller is designed to add a control signal to voltage magnitude and phase angle control loops. The proposed controller is installed based on linear quadratic regulator control approach. Moreover, An observer of full order is designed to estimate the power system states which are used to synthesize the control signal. Further, the power system responses after applying mechanical torque disturbance are obtained. The digital simulation results proves the effectiveness and powerful of the voltage magnitude and phase angle control of static phase shifter based on the proposed supplementary controller in terms of fast damping of SSR oscillation with less overshoot/undershoot.

7- REFERENCES

- [1] R.G.Farmer,AQ.L.Schwalb,and E.katz," Navagio project report on subsynchronous resonance analysis and solution" IEEE Trans. Vol.PAS-96, pp. 1226-1232, 1977.
- [2] Y.N.Yu,"Electric power system dynamic" (Academic Press,New York, 1983).

- [3] A. Ben Abdennour, R.M. Hammouda, and A.A. Al-Ohaly, "Countermeasures for Self-excited torsional oscillations using reduced order robust control approach," *IEEE Tran. On Power Systems*, Vol. 15, No.2, pp.779-784, May 2000.
- [4] Y.Y. Hau, and L.H. Jeng, "Damping of subsynchronous oscillations using adaptive controllers tuned by artificial neural networks" *IEE Proceedings-C* Vol. 142, No.4, pp. 415-420, July 1995.
- [5] S.V.J. Kumar, A. Ghosh, and Sachchidanand, "Damping of subsynchronous resonance oscillations with TCSC and PSS and their control interaction," *International Journal of Electric Power Systems Research*, Vol.54, pp.29-36, 2000.
- [6] K. Xing, and G.I. Kusic, "Damping subsynchronous resonance by phase shifter", *IEEE Trans. On Energy Conversion*, Vol. 4, No.3, pp.344-350, Sep. 1989.
- [7] Y.Y. Hsu, and C.J. Wu, "Design of PID static VAR controller for the damping of subsynchronous oscillations", *IEEE Trans. on Energy Conversion*, Vol. 3, No. 2, pp. 210-216, June 1988.
- [8] Y.Y. Hsu, and L. Wang, "Modal control of an HVDC system for the damping of subsynchronous oscillations," *IEE Proc. Vol.136, Pt.C. No. 2*, pp.7886, 1989.
- [9] S.K. Gupta, A.K. Gupta, and N. Kumar, "Damping subsynchronous resonance in power systems," *IEE Proc. Gener. Transm. Distrib. Vol. 149, No.6*, pp.679-688, Nov.2002.
- [10] A. Tabesh, and R. Iravani, "Frequency-response analysis of torsional dynamics," *IEEE Trans. on Power Systems*, Vol. 19, No. 3, pp.1430-1437, Aug.2004.
- [11] S. Lee, and C.C. Liu, "Damping torsional oscillations using a SIMO static VAR controller," *IEE Proceedings-C*, Vol. 140, No. 6, pp. 462-468, Nov. 1993.
- [12] S. Lee and J. Wu, "Application of superconducting magnetic energy storage unit on damping of turbogenerator subsynchronous oscillation", *IEE Proceedings-C*, Vol. 138, No. 5, pp. 419-426, Sep.1991.
- [13] C.J. Wu, and Y.S. Lee, "Application of simultaneous active and reactive power modulation of superconducting magnetic energy storage unit to damp turbine-generator subsynchronous oscillations" *IEEE Trans. On Energy Conversion*, Vol. 8, No.1, pp.63-70, March, 1993.
- [14] L. Wang, S.M. Lee, and C.L. Huang, "Damping subsynchronous resonance using superconducting magnetic energy storage unit," *IEEE Trans. on Energy Conversion*, Vol. 9, No. 4, pp. 770-777, Dec. 1994.
- [15] Y.L. Kang, G.B. Shrestha, and T.T. Lie, "Improvement of power system dynamic performance with the magnitude and phase angle control of static phase shifter" *International Journal of Electric Power System Research*, Vol. 55, pp. 121-128, 2000.
- [16] M. A. Abido, and Y.L. Abdel-Magid, "A tabu search based approach to power system stability enhancement via excitation and static phase shifter control," *International Journal of Electric Power Systems Research*, Vol. 52, pp.133-143, 1999.
- [17] A.M.A. Hamdan, "An investigation of the significance of singular value decomposition in power system dynamics" *International Journal of Elect. Power and Energy Systems*, Vol. 21, pp. 417-424, 1999.

إخماد الاهتزازات الرنينية تحت التزامنية باستخدام عنصر إزاحة الطور

في هذا البحث تم تطبيق عنصر من عناصر أنظمة النقل المرنة ذات التيار المتناوب وهو عنصر إزاحة الطور لإخماد الاهتزازات الرنينية تحت التزامنية . أمكن في هذه المقالة تغيير تزامني لمقدار و زاوية الجهد الذي يحدثه عنصر الإزاحة المقترح وذلك لتعديل جهد خط النقل المتصل به عنصر الإزاحة وبالتالي مسار القدرة الفعالة والغير فعالة تتعدل لمنع وتسريع إخماد الاهتزازات الرنينية تحت التزامنية. تم عمل نموذج رياضي لمنظومة القوى الكهربائية مع وجود عنصر إزاحة الطور المقترح. للتحكم في عنصر الإزاحة وتعديل مقدار واتجاه الجهد المقترح من هذا العنصر تم تصميم منظم اتوماتيكي على أساس منظم التربيع الخطى (LQR) . حيث أن هذا المنظم الاتوماتيكي يتطلب قياس كل حالات (states) النظام وبعض الحالات لا يمكن قياسها فان البحث اقترح تصميم اوبزيرفر (Observer) لإيجاد حالات النظام أثناء عمل المنظومة واستخدامهم في تكوين إشارة التحكم للمنظم (LQR) المقترح . ولتقييم أداء عنصر الإزاحة المحكوم بالمنظم المقترح تم إحداث اضطرابا بات فجائية وتغيير ظروف التشغيل لمنظومة القوى الكهربائية وإيجاد استجابة منظومة القوى المتمثلة في سرعة المولد التزامني وعزوم الحركة وزاوية الحمل. وتبين النتائج التي تم الحصول عليها قدرة عنصر الإزاحة المحكوم بالمنظم الاتوماتيكي المقترح في سرعة إخماد الاهتزازات الرنينية تحت التزامنية والحفاظ على استقرار منظومة القوى الكهربائية.