Application of Subsynchronous Damping Controller to Static Var Compensator

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Keywords

Subsynchronous Resonance (SSR), Static Var Compensator (SVC), Thyristor Controlled Reactor (TCR), Thyristor Switched Capacitor (TSC).

Abstract

This paper proposes a new auxiliary Subsynchronous Damping Controller (SSDC) for the Static Var Compensator (SVC) to damp out subsynchronous oscillations in power system containing series compensated transmission lines. The arrival of Wide Area Measurement (WAM) technology has made it possible to measure the states of a large power system interconnected with synchronized Phasor Measurement Units (PMU). This paper presents the idea of using remote signals obtained from PMU to damp SSR. An auxiliary subsynchronous damping controller (SSDC) has been proposed for a SVC, using the generator rotor speed deviation signal as the stabilizing signal to damp subsynchronous oscillations. Sturdiness of the controller has been examined by applying the disturbances in the system that causes significant changes in generator's operating point. The IEEE Second Benchmark (SBM) model is used for the analysis and the SVC is simulated using the Power System Block set (PSB) in the MATLAB/Simulink environment.

INTRODUCTION

Since 1950, to increase the transmitted power capability through long transmission line (more than 150 mile), series capacitors as an efficient and effective solution approach have been employed. Steady-state and transient limits could be increased significantly by applying the series capacitors. Furthermore, the series capacitors could potentially act as a perfect mean for var and voltage controlling.

It was believed that almost 70% of the series components could be used for transmission lines without considerable concerns. However this issue has been changed by shaft damages in 1970 and 1971 in a 750 MW cross compound Mohave turbine-generator in southern Nevada. As a conclusion, it has been cleared that an adverse interaction between the series compensated electrical system and the spring-mass mechanical system of the turbine-generators can be created by the series capacitors. The happened incident is known as the subsynchronous resonance (SSR) which arises from the resonant condition. It should be mentioned that the resonant condition has a natural frequency below the fundamental frequency of the power system [1]-[3].

Numerous researches have been performed in the area of damping the SSR phenomenon which are categorized generally in two main groups. The first group consists of Flexible AC Transmission Systems (FACTS) and the second one are about generator excitation system and Power System Stabilizer (PSS). In order to mitigate SSR this paper has proposed an application based on FACTS controller.

Proper performance of the FACTS controller to moderate and mitigate the subsynchronous resonances has introduced as a practical solution. Moreover, an optimal SSDC for SVC with genetic algorithm method has been designed [4]. To modulate the reactive current reference of STATCOM, some designers have used thevenin voltage signal [5]. The thevenin voltage signal is achieved from reactive current signals the locally available STATCOM bus voltage. Using the generator rotor speed deviation signal to modulate the reactive current reference of STATCOM, a subsynchronous damping controller has designed too [6]. Since the generator rotor speed signals are practically available, it could be a great tool for SSDC in ref [7] however, SSDC are designed on the generator excitation system.

Pole assignment method has been implemented to control all the SSR modes [8]-[10]. Yu, et al. employed the method of pole assignment using state feedback [8]. The most of the state variables are inaccessible. Accordingly, the applied method was completely impractical. Dominating the mentioned issue, an output feedback excitation control scheme has been presented [9]. However due to usage the constant feedback control scheme; practically measuring seven state variables containing some signals are still laborious. Wang and Hsu [10] have used a dynamic output feedback controller. The parameters of the dynamic compensator are adjusted by displacement all the torsional modes to certain pre-specified locations. Although the controller is able to damp all the modes, by increasing the compensation ratio greater than 60%, mode-1 behaves unstably.

The latest development in the WAM technologies and adopting PMUs, the synchronous phasors and control signals can be conveyed fast with a sampling rate in the range of 30 Hz. It worthwhile to notice that in order to transfer the measured states to the control center, the dedicated fiber-optic communication lines have been employed [11]-[13].

Concerning inter-area oscillations damping, information of the entire power system network are used to design Power System Stabilizers (PSS) and FACTS Controllers [14]. In a large interconnected system, to transfer the generator speed to the FACTS Controller, the dedicated fiber-optic link has been used [15].

In this paper, a pure derivative controller with capability to damp all subsynchronous modes will be introduced. In the proposed controller, the generator rotor speed deviation signal which is practically measurable is applied as the input signal of the SSDC controller in SVC. The advantages of the proposed method could be the simplicity and easy implementation. A wide range of series compensation ratios can be covered by the offered controller. In addition, it can improve damping ratios of all modes. The performance and operation of the designed controller, not only in linear analysis, but also in transient simulations considering nonlinear model of the system will be assessed. Additionally, the robustness of the controller will be analyzed by facing the system with disturbances which leading the controller to significant changes in generator operating point.

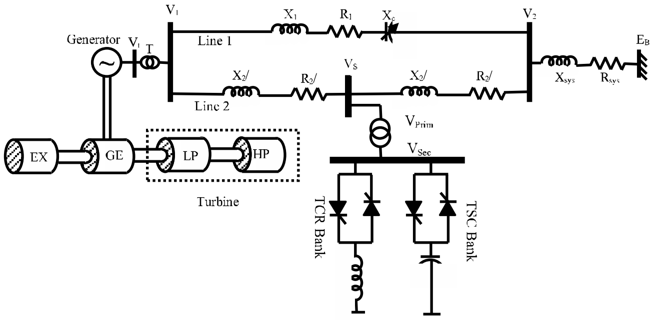


Fig.1.Schematic representation of IEEE SBM system 1-Model with SVC.

SYSTEM MODEL

The IEEE second benchmark SBM system model is evaluated for the SSR studying that its schematic is shown in Fig. 1. The model comprises of a synchronous generator which is connected to a very large network. The network is approximated by an infinite bus. The connection has been done through a transformer and two parallel transmission lines. Line one is compensated by series capacitors. In addition, the mechanical system is modelled by 3-masses: mass1 = generator; mass2 = low pressure turbine (LP) and mass3 = high pressure turbine (HP).

The modeling of hydraulic turbine and turbine control model for dynamic studies has been evaluated by an IEEE Committee [17]. In order to realize the proposed model and make it practical, some aspects are considered. It means, the excitation systems consists of Automatic Voltage Regulator (AVR), Excitation System Stabilizer (ESS) and Power System Stabilizer (PSS) [7]. The assessments are performed in accordance with the following assumptions and initial operating condition [5], [6].

- The delivered power to the transmission line by the synchronous generator is 1 p.u. In addition, the generator voltage and infinite bus voltages are set at 1 p.u.
- The series capacitor compensation level provided is specified at 52% of the reactance X1.
- Concerning effective and efficient utilization of the SVC abilities and capabilities, a fixed shunt capacitor is connected to the SVC bus in the middle of the transmission line No. 2.
  The midpoint voltage of the transmission line in steady state condition should be maintained at 1 p.u. Hence in the case study without SVC, the value of the fixed shunt capacitor is calculated 160.37 Mvar. While, in the case study with SVC, the shunt capacitor provides 100 Mvar and the SVC produce the rest of the required reactive power. The rating of the SVC is considered 100 Mvar.
- A 10% step decreasing is applied in the mechanical input torque at 0.5 second and it will be removed after 1 second.

SVC MODEL

The SVS is a shunt device from FACTS family which consists of the power electronic equipment. In order to voltage regulation, SVC absorbs or generates reactive power. The desired SVC consists of a 100 Mvar TCR bank and 50 Mvar TCS bank. The SVC as is shown in Fig. 1 is connected in the middle of line 2 through a coupling transformer 500 kV/16 kV (Yg/d). The three phase bank has Delta connection. Hence during normal balanced operation, the zero-sequence tripplen harmonics (3rd, 9th,...) remain inside the delta. Consequently injected harmonics in the power system will be decreased.

Switching the TSC's can induce a wide range of discrete capacitive variations in the secondary reactive power (0-100 Mvar). The mentioned variations are in the 50 Mvar steps and at 16 kV. Since, the TCR phase control can cause continues inductive variations up to 100 Mvar.

SVC CONTROL SYSTEM

SVC control system which contains SSDC is shown in Fig. 2. The primary voltage magnitude with $V_{abc(Prim)}$ with positive sequence and fundamental-frequency is measured. Producing the error signal, the measured value is compared with the reference voltage (V_{ref}). The primary susceptance (B_{SVC}) will be achieved by passing the error through the PI regulator. To determine the TCR firing angle and the status (on/off) of the three TSC branches, the distribution unit employs B_{SVC}.TCR susceptance (B_{TCR}) as a function of the firing angle can be presented in this form:

$$B_{TCR} = \frac{2(\pi - \alpha) + \sin(2\alpha)}{\pi} \qquad (1)$$

where B_{TCR} is the TCR susceptance in p.u of rated TCR (100 Mvar). In order to monitor the system frequency variation, the associated Phase Locked Loop (PLL) is employed. The SVC control system consists of two main parts. A synchronizing system with three PLLs synchronized on line-to-line secondary voltages $V_{abc(sec)}$ and a pulse generator. The Pulse generator produces and sends appropriate pulses to the 24 thyristors (6 thyristors per three-phase bank).

Generally, SVC works in two different operational modes:

1) Voltage regulation mode: In this case V_{ref} is defined by an external controller. The output voltage will be kept constant in V_{ref} by the SVC with absorbing or generating reactive power. It is implemented by the PI regulator.

2) Var regulation mode: The reactive power produced by the SVC is fixed and the SVC susceptance is kept constant. It should be mentioned that in this mode, the presence of voltage regulator is not necessary. Hence, the B_{SVC} is applied directly by an external controller to the SVC.

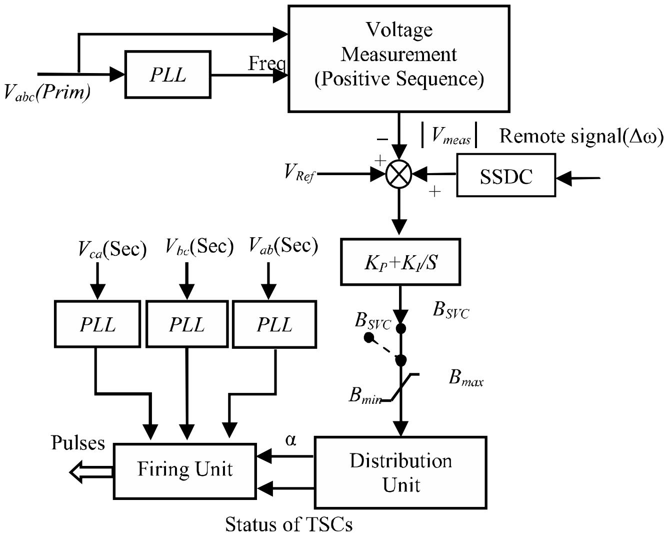


Fig. 2. SVC control system.

SIMULATION RESULTS

Modeling has been implemented by MATLAB/Simulink. In Fig.3, only one TSC bank is shown. The achieved results from transient simulation of the nonlinear system which contains designed SSDC will be presented in the following. In the simulation compensation ratio of the line, 52% has been assumed. As it has been already mentioned, the simulation for 10% decrease in the input mechanical torque applied at 0.5 s and removed at 1 s has been performed.

The result of the simulation with SVC and voltage control and without SSDC is shown in Fig. 4. It is clear that the system is unstable due to the oscillations in LP-GEN section torque grows with time. Simulation results, when SSDC is applied in SVC are presented in Fig. 5. As it is shown, by using the SSDC, of LP-GEN section torque oscillation is damped after a short time and the system becomes stable. Furthermore as it has been expected, in order to regulate the voltage in the installation place at 1 p.u, injected reactive power by SVC is 60 Mvar. Additionally, analysis's results approve that by increasing the K_P amplitude, the mechanical modes become more stable.

The stability behavior of the system is presented in Fig. 6. It shows the LP-GEN section torque in the voltage control mode. Comparing obtained results from $K_P = 2$ and $K_P = 4$, obviously approve that by increasing the K_P amplitude, damping rate of the oscillations increases consequently.

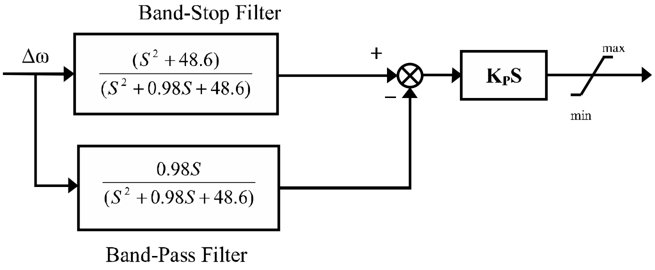
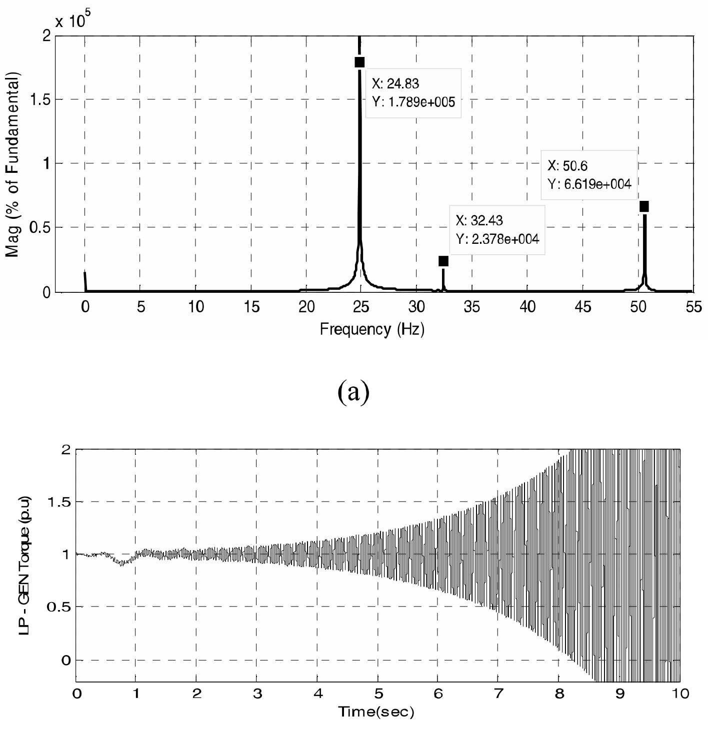


Fig.3. Block diagram of the designed SSDC

In accordance with the simulation results, the mechanical damping rates increase significantly by increment in the amplitude of K_P. While the zero modes damping rates decline. It could be due to SSDC without filter.

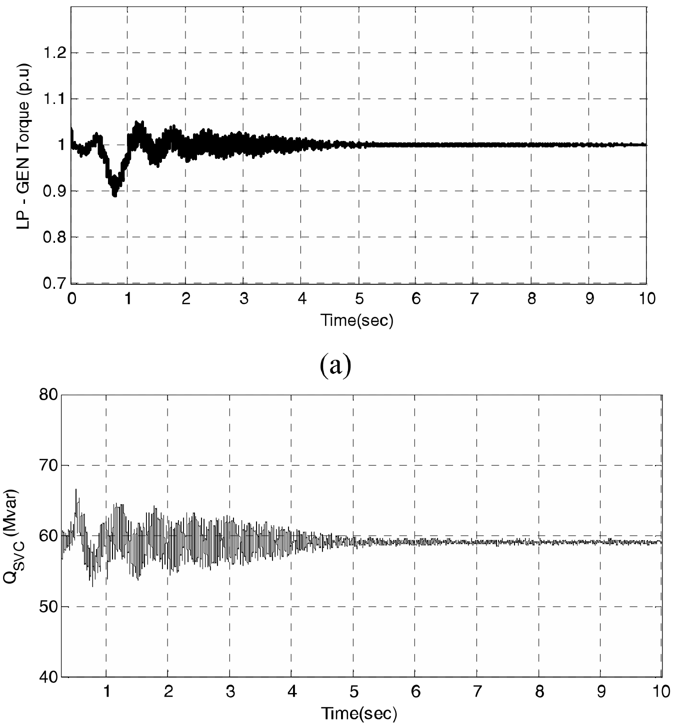
FFT analysis on the $\Delta\omega$ signal of generator when $K_P = 6$ approves this matter explicitly. As it is clear, although the mechanical modes increase in the time steps, zero modes amplitude decline.



(a)

(b)

Fig.4. a) FFT analysis of $\Delta\omega$. b) Variation of LP-Gen section torque for changing pulse in the input mechanical torque (SVC with the voltage control and without the SSDC).



(a)

(b)

Fig. 5. Variation of LP-GEN section torque(a) and SVC reactive power (b)for pulse change in input mechanical torque (SVC with SSDC (K_P=2)).

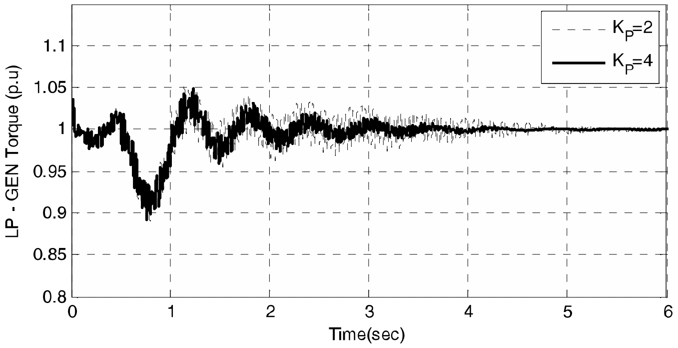


Fig. 6. Variation of LP-GEN section torque for pulse change in input mechanical torque (SVC with SSDC (K_P=4 and K_P=2)).

ROBUSTNESS VERIFICATION

The operating conditions of the transmission lines can experience considerable changing due to serious faults in. In order to verify the designed controller performance, the system has been faced with this type of disturbances.

Hence, considering the designed controller robustness would be the next step. It should be assessed by considering a large disturbance in the transmission line. A well designed controller supposed to represent a satisfactory performance during changing in the operation conditions.

The designed controller has been simulated in some new operating conditions to be sure about its robustness. It is assumed that a single-line-to ground (a-g) fault is occurred at the beginning of the line 2 at t=0.5 s and cleared at 0.62 s.

The system without any supplementary controller would become obviously unstable. The variation of LP-Gen section torque with the designed SSDC has been considered (Fig. 8). As shown in the Fig. 8 the designed SSDC have successfully stabilized the system even when a large disturbance affected the system.

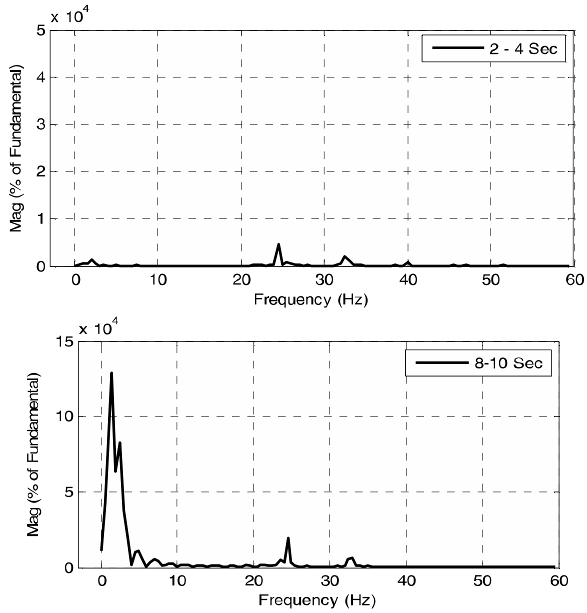


Fig. 7. FFT analysis of Δω signal (SVC with SSDC (without high-pass filter, K_P=6)).

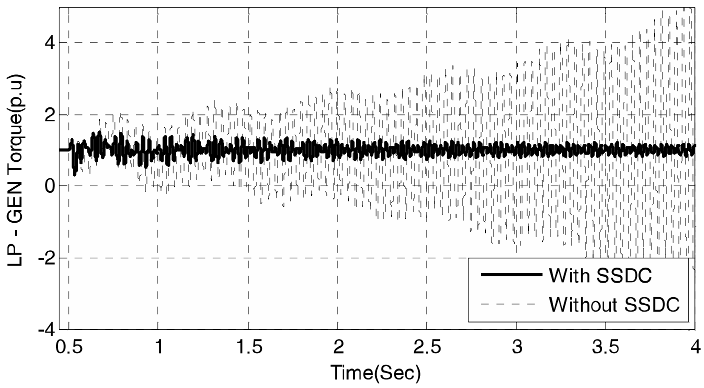


Fig.8. Variation of LP-Gen section torque for a-g fault.

CONCLUSIONS

A simple controller has been proposed for SVC to damp the subsynchronous oscillations. The performance of the designed controller has been verified using several testing scenarios. Some of the main results from the simulations are listed below:

- The designed controller has been applied successfully for damping all the unstable torsional modes.
- A wide range of compensation ratios is covered by using the offered SSDC.
- Only one signal which is easily measurable is applied in control design.
- Performance of the designed SSDC is validated using simulation results as well as the nonlinear transient simulations.
- The proposed controller uses an unsophisticated and easy to implement idea to cope with the SSR phenomenon.

Simplicity and practicality of the proposed controller with its excellent performance make it ideal to be implemented in real power plants.

References

[1] P. M. Anderson and R. G. Farmer, Subsynchronous resonance, in Series Compensation of Power Systems, PBLSH, San Diego, 1996, chap. 6.

[2] IEEE Power System Engineering Committee, "Analysis and Control of Subsynchronous Resonance," IEEE Power Engineering Society Winter Meeting and Tesla Symposium, 1976.

[3] R. G. Farmer, A. L. Schwalb and E. Katz, "Navajo Project Report on Subsynchronous Analysis and Solution," IEEE Trans., Vol. PAS-96, pp. 1226-1232, 1977.

[4] X. Xie, Q. Jiang and Y. Han , "Damping multimodal subsynchronous resonance using a static var compensator controller optimized by genetic algorithm and simulated annealing" Euro.Trans. Electr. Power. Article first published online: 30 DEC 2011, DOI: 10.1002/etep.655.

[5] K. R. Padiyar and N. Prabhu, "Design and Performance Evaluation of Subsynchronous Damping Controller With STATCOM," IEEE Trans. Power Delivery, vol. 21, no. 3, pp. 1398-1405, Jul. 2006.

[6] A. Ghorbani, B. Mozaffari and A. M. Ranjbar, "Application of subsynchronous damping controller (SSDC) to STATCOM" Electrical Power and Energy Systems, Vol. 43, pp. 418-426. 2012.

[7] A. Ghorbani and S. Pourmohammad, "A novel excitation controller to damp subsynchronous oscillations" Electrical Power and Energy Systems, Vol. 33, pp. 411-419, 2011.

[8] Y. N. Yu, M.D. Wvong, and K.K. Tse, "Multi-mode wide-range subsynchronous resonance stabilization", Paper A78 554-8, presented at the IEEE/PES 1978 Summer Meeting, LosAngeles, 1978.

[9] A. Yan and Y. N. Yu, "Multi-mode stabilization of torsional oscillation using output feedback excitation control", IEEE Trans. PAS, Vol. 101, pp. 1245-1253, 1982.

[10] Y. Y. Hsu and L. H. Jeng, “Damping of subsynchronous oscillations using adaptive controllers tuned by artificial neutral network” IEE Proc.-Gener. Transm. Distrib., Vol. 142, No. 4, 1995.

[11] I. Kamwa, R. Grondin, and Y. Hebert, "Wide-area measurement based stabilizing control of large power systems—a decentralized/hierarchical approach," IEEE Trans. Power Syst, vol. 16, no. 1, pp. 136–153, Feb. 2001.

[12] J. Bertsch, C. Carnal, P. Korba, L. Broski, andW. Sattinger, "Experience and benefits of systems for wide area monitoring," in Proc. 6th Annu. Western Power Delivery Automation Conf., Spokane, WA, Apr. 2004.

[13] G. Heydt, C. Liu, A. Phadke, and V. Vittal, "Solutions for the crisis in electric power supply," IEEE Comput. Appl. Power, vol. 14, no. 3, pp. 22–30, Jul. 2001.

[14] R. Majumder, B. Chaudhuri, B. C. Pal and Q. C. Zhong, "A Unified Smith Predictor Approach for Power System Damping Control Design using Remote Signals," IEEE Trans. Control Systems Technology, vol. 13, no. 6, pp. 1063-1068, Nov. 2005.

[15] J. H. Chow, Juan J. Sanchez-Gasca, Haoxing Ren and Shaopeng Wang, "Power System Damping Controller Design using Multiple Input Signals," IEEE Control System Magazine, pp. 82-90, Aug. 2000.

[16] IEEE Subsynchronous resonance working group, "Second benchmark model for computer simulation of subsynchronous resonance," IEEE Transactions on Power Apparatus and Systems, vol. PAS-104, no. 5, pp. 1057-1066, 1985.

[17] IEEE committee report, "Dynamic models for steam and hydro turbines in power system studies," IEEE Transactions on Power Apparatus and Systems, Vol.PAS-92, No.6, pp.1904-1915, 1973.

[18] A. N. G. Hingorani and L. Gyugyi, *Understanding FACTS Concepts and Technology of Flexible AC Transmission Systems*, New York: IEEE Press, 2000.

[19] SimPowerSystems Toolbox ver. 5.1, for use with Simulink, User’s Guide. The MathWorks, Inc., 2009.

[20] A. Ghorbani, M. Khederzadeh and B. Mozafari, “Impact of SVC on the protection of transmission lines” Electrical Power and Energy Systems, Vol. 42, pp. 702-709, 2012.

[21] K. R. Padiyar, *Analysis of Subsynchronous Resonance in Power Systems*, Department of Electrical Engineering, India Institute of Science, 1999.