Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Mitigation of Subsynchronous Oscillations by 48-Pulse VSC STATCOM Using Remote Signal

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***Abstract*—Series compensated power system may lead to a very unusual problem known as Subsynchronous Resonance (SSR). Flexible AC Transmission Systems (FACTS) controllers are widely applied to mitigate subsynchronous oscillations. The Static Synchronous Compensator (STATCOM) is a shunt device of the FACTS family using power electronics to control power flow and improve transient stability on power grids. With the advent of Wide Area Measurement (WAM) technology, it is possible to measure the states of a large interconnected power system with synchronized Phasor Measurement Units (PMU). In this paper the concept of using remote signals acquired through PMU has been proposed to damp SSR. An auxiliary subsynchronous damping controller (SSDC) for a STATCOM using the remote accelerating power of generator signal as the stabilizing signal has been designed to damp subsynchronous oscillations. This paper deals with a cascaded multilevel converter model, which is a 48-pulse (three levels) source converter. The voltage source converter described in this paper is a harmonic neutralized, 48-pulse GTO converter. The IEEE Second Benchmark (SBM) model is considered for the analysis and the complete digital simulation of the STATCOM within the power system is performed in the MATLAB/Simulink environment using the Power System Blockset (PSB).**

***Index Terms*— Flexible AC Transmission Systems (FACTS), Subsynchronous Resonance (SSR), 48-pulse Gate Turn-Off (GTO) thyristor model STATCOM, Subsynchronous Damping Controller (SSDC), Wide Area Measurement (WAM), Phasor Measurement Unit (PMU).**

I. Introduction

Subsynchronous resonance is a power system phenomenon where the electric power system exchanges its energy with turbines at one or more frequencies below the synchronous frequency, when the electric network is compensated with series capacitors. The problem of torsional interaction has been identified to take place when the electric resonant frequency is near the complement of one of the torsional mode frequencies of the turbine-generator shaft system. Under such circumstance the shaft will oscillate at this natural frequency [1], [2]. Successful application of FACTS controllers has been reported in past to mitigate subsynchronous resonance [3]. In [4] the effectiveness of an auxiliary signal designated as Computed Internal Angle (CIA), which modulates the voltage reference of STATCOM, is investigated. In [5] a SSDC is designed and added to STATCOM to enhance the torsional mode damping of the system. The SSDC in [5] uses the thevenin voltage signal to modulate the reactive current reference of STATCOM. The thevenin voltage signal is derived from the locally available STATCOM bus voltage and reactive current signals.

The recent advances in WAM technologies using Phasor Measurement Units (PMUs) can deliver synchronous phasors and control signals at a high speed of about a 30 Hz sampling rate [6]-[8]. Dedicated fiber-optic communication lines are used to transmit these measured states to the control centre. This information of the entire power system network is used to design Power System Stabilizers (PSS) and FACTS Controllers to damp inter-area oscillations [6], [9]. It has been reported in [10] that through a dedicated fiber-optic link the generator speed can be transmitted to the location of the FACTS Controller to damp inter-area oscillations in a large interconnected system. In [11] the remote generator speed signal is utilized by a Static VAR Compensator (SVC) located at the mid-point of a, transmission line and a SSDC to damp subsynchronous oscillations.

In this paper, the damping of subsynchronous oscillations using STATCOM, which is provided at the middle of the transmission line, is presented. The STATCOM based on a full model comprising a 48-pulse Gate Turn-Off thyristor voltage source converter for combined reactive power compensation and voltage stabilization of the electric grid network [12]. In this work the concept of using remote signal acquired through PMU has been proposed to damp SSR. In addition an auxiliary SSDC is designed and added suitably to enhance the torsional mode damping of the system and SSDC using the remote accelerating power of generator signal as the stabilizing signal. Simplicity and ease of implementation are advantages of the proposed method. The effect of signal transmission delay is also discussed.

The outline of this paper is as follows: Section II describes the digital simulation model. The simulation results are presented in section III. Section IV describes the effect of signal transmission delay. The conclusion is drawn in section V.

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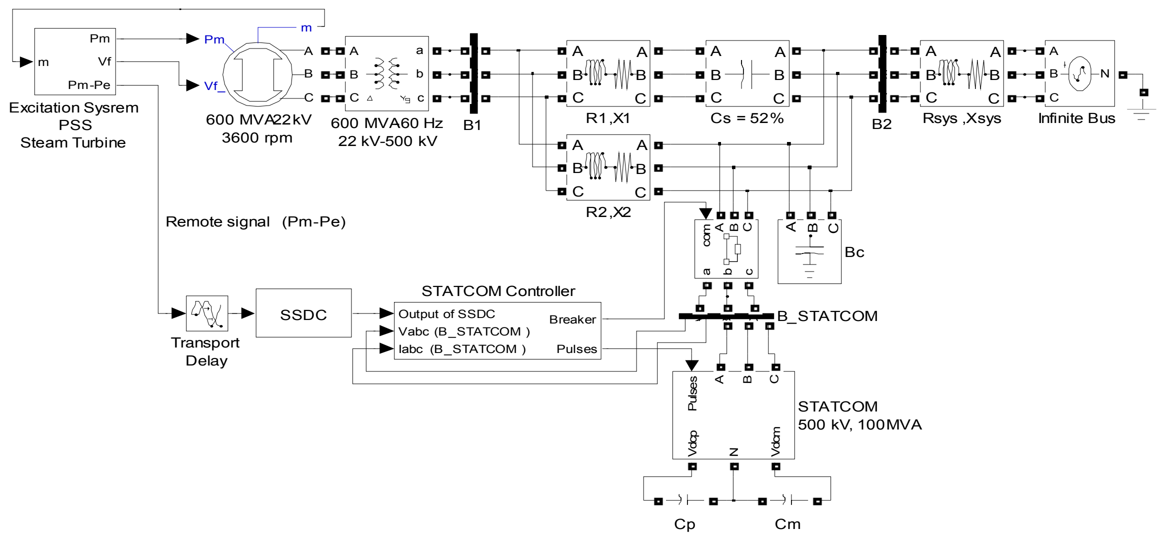

Fig. 1. IEEE SBM with STATCOM performed in the MATLAB/Simulink environment using the PSB.

II. Digital Simulation Model

The digital simulation is performed using the MATLAB/Simulink software environment and the Power System Blockset (PSB). A complete model using the 48-pulse digital simulation of the STATCOM within a power system is presented in this paper. The control process is based on a decoupled current control strategy using both the direct and quadrature current components of the STATCOM [12].

A. Power System Description

The system considered is a modified IEEE SBM [13]. Modeling the unified ac grid sample system with STATCOM connected at the electrical center of the transmission line as shown in Fig. 1 (the model built with PSB). The modeling aspects of the electromechanical system comprising the generator, the mass-spring mechanical system, excitation system (the standard IEEE AVR system ST1A introduced in [14]), Power System Stabilizer (PSS) [15], the transmission line containing the conventional series capacitor. The analysis is carried out based on the following initial operating condition and assumptions [4], [5]:

1) The generator delivers 1 p.u. power to the transmission system and the magnitude of the generator and infinite bus voltages are set at 1.00 p.u.
2) The dynamics of the turbine-governor systems are neglected and the input mechanical power to the turbine is assumed constant.
3) The compensation level provided by the series capacitor is set at 52% of the reactance X_l.
4) For the case studies without STATCOM, the value of fixed shunt capacitor (B_C) is selected such that, the midpoint voltage is set at 1 p.u. in steady state (shunt capacitor provides required power of 160.37 MVAr to maintain magnitude of voltage 1 p.u.)
5) For the case studies with STATCOM, shunt capacitor provides 100 MVAr and the STATCOM supplies additional reactive power required to maintain the magnitude of midpoint voltage 1 p.u. The rating of STATCOM is selected as ± 100 MVAr.
6) A step decrease of 10% mechanical input torque applied at 0.5 sec and removed at 1 sec is considered.

B. Modelling of STATCOM

The STATCOM is a shunt device of the FACTS family using power electronics. It regulates voltage by generating or absorbing reactive power. The voltage source converter described in this paper is a harmonic neutralized, 48-pulse GTO converter. It consists of four three-phase, three-level inverters and four phase-shifting transformers. In the 48-pulse voltage source converter, the dc bus V_{dc} is connected to the four three-phase inverters. The four voltage generated by the inverters are applied to secondary windings of four zig-zag phase-shifting transformers connected in Y or Δ [12].

The 48-pulse converter model comprises four identical 12-pulse GTO converters interlinked by four 12-pulse transformers with phase-shifted windings. Fig. 2 depicts the schematic diagram of the 48-pulse GTO's voltage source converter model.

A dc capacitor is connected to the four 3-level inverters, the magnitude of square-wave voltage can be $+V_{dc}$, 0, $-V_{dc}$. The duration of zero voltage in each quarter cycle is defined as "dead angle" γ, and it can be adjusted from 0º–90º. The fundamental component of voltage source inverter has the amplitude of :

$$V_{X,n} = \frac{2}{\pi} V_{dc} \cos\left(\frac{\pi}{24}\right) \times \cos\gamma \tag{1}$$

As seen from (1), the magnitude of the output voltage can be adjusted through changing the value of dead angle γ and/or the dc voltage of the capacitor. The phase angle α of the output voltage can be adjusted by using the input signal from the pulse generator [16].

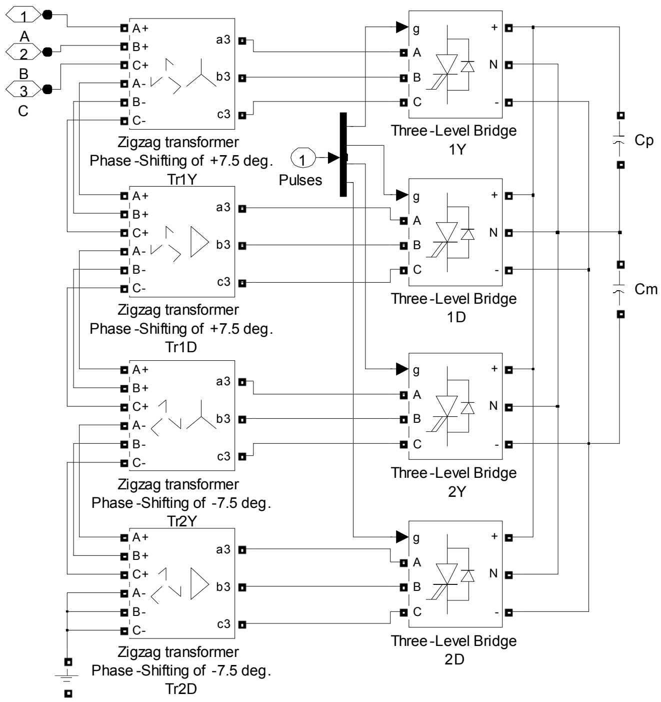

Fig. 2. 48-pulse GTO's voltage source converter.

C. STATCOM Control Model

The control of STATCOM (Fig. 3) is used to operate the voltage source inverter to inject or absorb reactive power to regulate the connecting point voltage to the setting value V_{ref}. The decoupled control system is based on a full d-q decoupled current control strategy using both direct and quadrature current components of the STATCOM ac current [12].

A phase locked loop (PLL) synchronizes on the positive sequence component of the three-phase terminal voltage at interface Bus-2. The output of the PLL is the (ωt) that used to measure the direct axis and quadrature axis component of the ac three-phase voltage and current. The outer regulation loop comprising the ac voltage regulator provides the reference current (I_{qref}) for the current regulator that is always in quadrature with the terminal voltage to control the reactive power. The voltage regulator is a proportional plus integral PI controller. The current regulator is also PI controller [12], [16]. Firing Pulses Generator generates pulses for the four inverters from the PLL output (ωt) and the current regulator output (α angle).

The STATCOM can be operated in two different modes:

1) In voltage regulation mode:
   In this mode the STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system.
2) In var control mode:
   In this mode the STATCOM reactive power output is kept constant. In such a case, the reference current (I_{qref}) is no longer generated by the voltage regulator and that remains constant (Fig. 3).

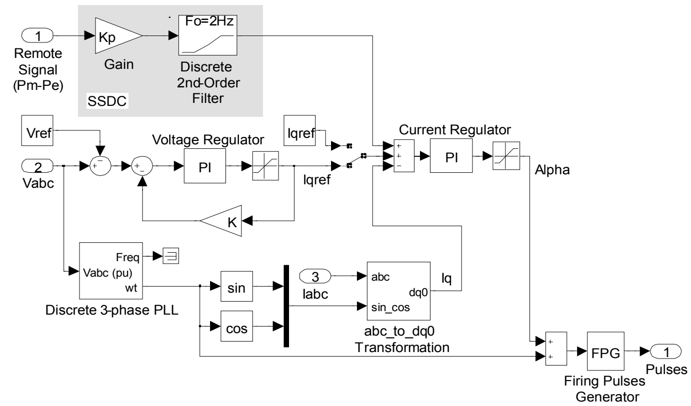

Fig. 3. Control model of STATCOM with SSDC.

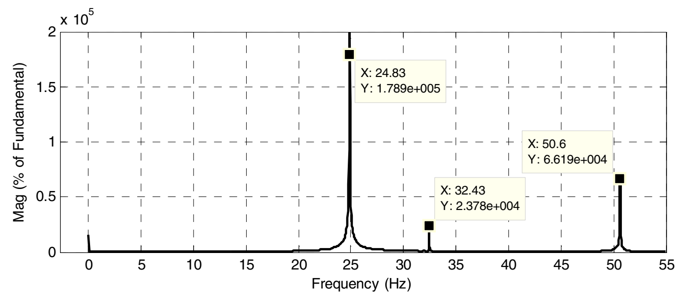

Fig. 4. FFT analysis accelerating power of generator signal.

D. Design of SSDC

The different signals generally considered as the input signals to the auxiliary controller are line real power flow, line current magnitude, bus frequency, bus voltage magnitude etc [3]. In this paper, the remote accelerating power of generator signal as the stabilizing signal. It is found by FFT analysis with MATLAB that modes exist in the accelerating power of generator signal and the torque signals of various turbine stages (Fig. 4).

The reactive current can also be modulated by the output of a SSDC (Fig. 3). The SSDC controller concludes a K_P booster, high-pass filter. K_P booster is used for amplifying the remote signal. Transient simulations show, by implementing the amplified accelerating power signal of generator, we can stabilize the unstable modes. The FFT analysis on the accelerating power signal of generator shows that increase of K_P makes the mechanical modes more stable but decreases the stability of zero mode. We can cope this problem by transmitting the accelerating power signal of generator from a high-pass filter and omitting the zero frequency mode. More descriptions can be found in simulation results.

III. Simulation Results

System-1 of the IEEE SBM model is used for the analytical and computer simulation studies [13]. This system consists of a 600 MVA, 2 pole, 22 kV steam turbine-generator set which is connected to infinite bus through a three line network in

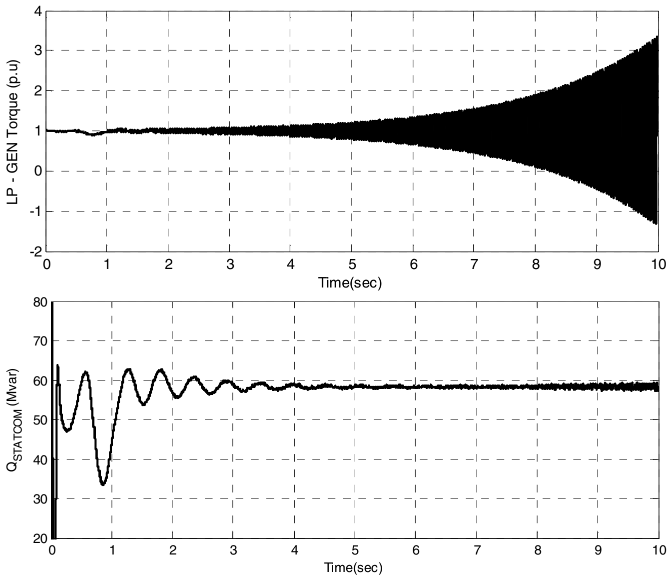

Fig. 5. Variation of LP-GEN section torque and STATCOM reactive power for pulse change in input mechanical torque (STATCOM with voltage control and without SSDC).

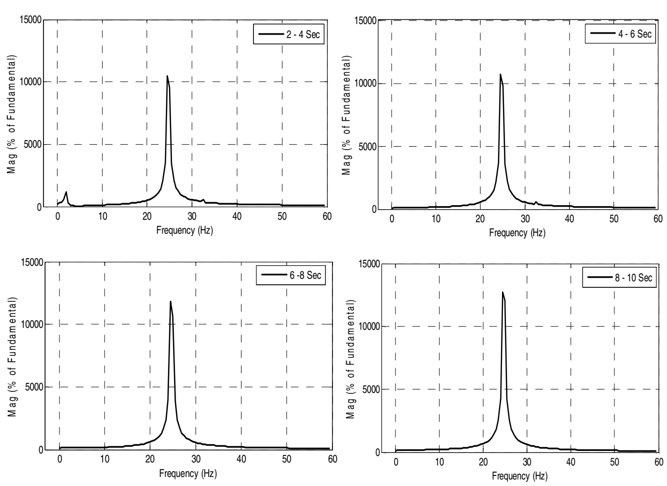

Fig. 6. FFT analysis accelerating power of generator signal (STATCOM with voltage control and without SSDC).

which one of two parallel lines is capacitor compensated as shown in Fig. 1. The shaft of the turbine-generator set is comprised or four masses: exciter (EXC), generator rotor (GEN), one low-pressure turbine (LP) and one high-pressure turbine (HP). The shaft system has three torsional modes at frequencies of 24.83 Hz, 32.43 Hz and 50.6 Hz (Fig. 4).

When the series compensation in line-1 is taken to be X_c=0.24 p.u (52% of X_l) the complement of electrical resonance frequency matches with the critical torsional mode-1 of the IEEE SBM Sys-1 model and the system becomes unstable when the net damping is low [17]. Hence, this operating mode is considered for the analysis with and without STATCOM. Fig. 4 depicts the FFT plot for this series compensation. It shows a maximum destabilization for 24.83 Hz mode (mode 1). The simulation results for 10% decrease in the input mechanical torque applied at 0.5 s and removed at 1 s with STATCOM with voltage control is shown in Fig.5.

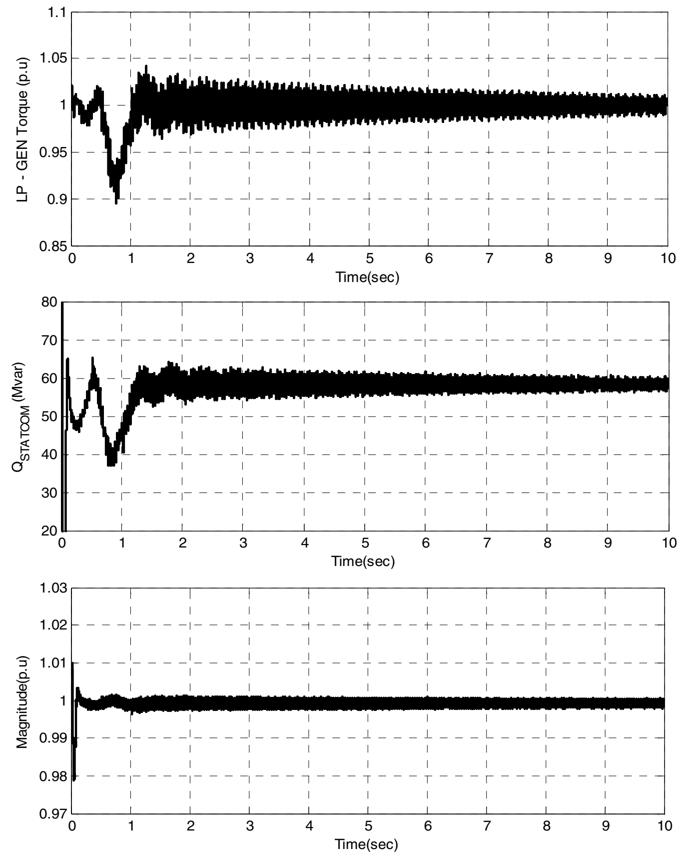

Fig. 7. Variation of LP-GEN section torque, STATCOM reactive power and BUS-2 voltage for pulse change in input mechanical torque (STATCOM with voltage control and with SSDC (K_P=2)).

It is clear from Figs. 5 that, the system is unstable as the oscillations in LP-GEN section torque and rotor speed deviation grows with time.

The FFT analysis of the accelerating power of generator signal is performed among 2–10 s with the time spread of 2 s. The results of fast Fourier transform (FFT) analysis are shown in Fig. 6. Referring to Fig. 6, it is observed that as the time progresses, mode-1 component increases while all other torsional mode components decay.

As it was due, mode-1 is unstable for 52% compensation and STATCOM, in voltage control mode, couldn't stabilize it. The result of simulation when the STATCOM is set in var control mode is not shown however it is like the voltage control mode results.

Simulation results, when SSDC is implementing to STATCOM and for both working modes of it, are shown in Fig. 7 and Fig. 8. As it demonstrated in figures, system is stable and oscillation of LP-GEN section torque is damped in a few seconds. Also as it was expected, for regulating the voltage of installation place in one per unit, the injected reactive power by STATCOM becomes 60 MVAr. According to Fig. 8, for the same K_P, damping rate of oscillations when STATCOM is in the var control mode is more than when it is in the voltage control mode.

When the STATCOM is operating in capacitive mode, the

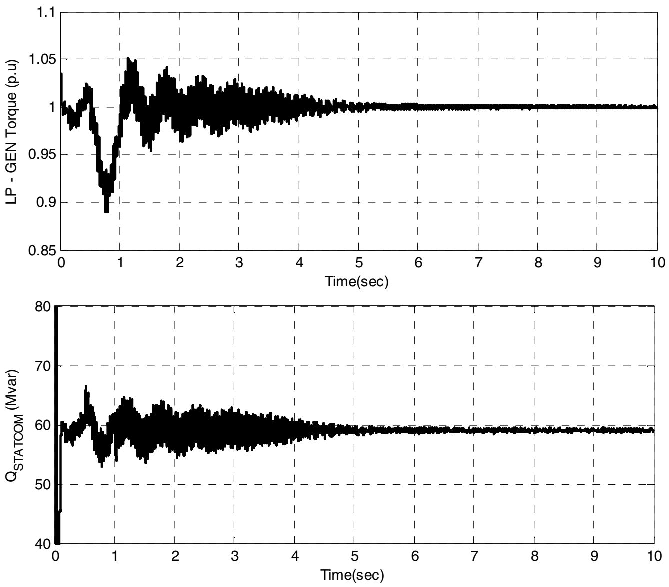

Fig. 8. Variation of LP-GEN section torque and STATCOM reactive power for pulse change in input mechanical torque (STATCOM with var control and with SSDC (K_P=2)).

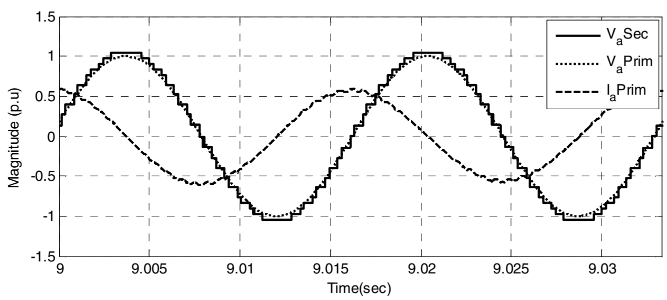

Fig. 9. Steady-state voltages and current for STATCOM in capacitive operation. (STATCOM with voltage control and with SSDC (K_P=2)).

48-pulse secondary voltage generated by inverters is higher than the primary voltage and in phase with primary voltage. Current is leading voltage by 90°; the STATCOM is therefore generating reactive power (Fig. 9).

As it was said, the mechanical modes become more stable by increase in amplitude of K_P. Increment of stability can be seen in Fig. 10 where LP-GEN section torque and reactive power of STATCOM is demonstrated in the voltage control mode and K_P=5. By comparing Fig. 7 and Fig. 10 it can be seen that by bigger K_P, the damping rate of oscillations increases. Fig. 11 shows the FFT analysis on the accelerating power signal of generator when STATCOM is in voltage control mode and K_P=5. It can be seen that after seconds the amplitude of mechanical modes decrease and become smaller than previous sections which shows system stability.

More increment in amplitude of K_P, makes the mechanical damping rates increase but zero mode damping rate declines. FFT analysis on the accelerating power signal of generator when STATCOM is in voltage control mode and K_P=6 (Fig. 12) shows this matter explicitly. As it is shown in Fig. 12, in time steps, amplitude of mechanical modes decrease but amplitude of zero mode increases.

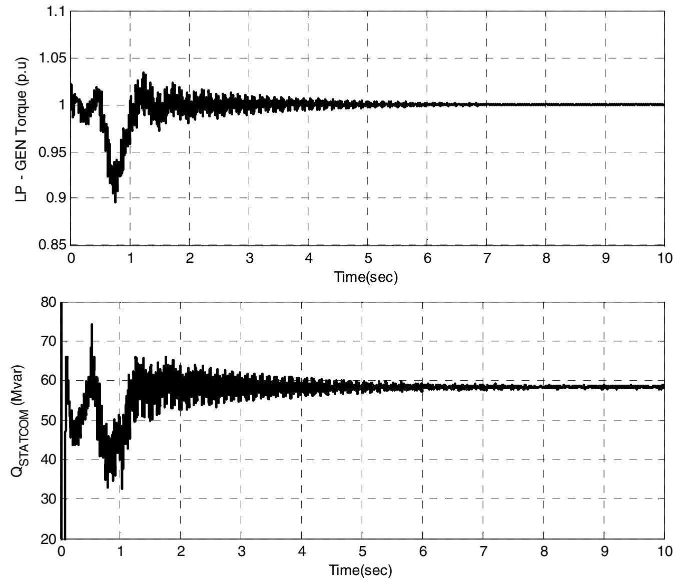

Fig. 10. Variation of LP-GEN section torque and STATCOM reactive power for pulse change in input mechanical torque (STATCOM with voltage control and with SSDC (K_P=5)).

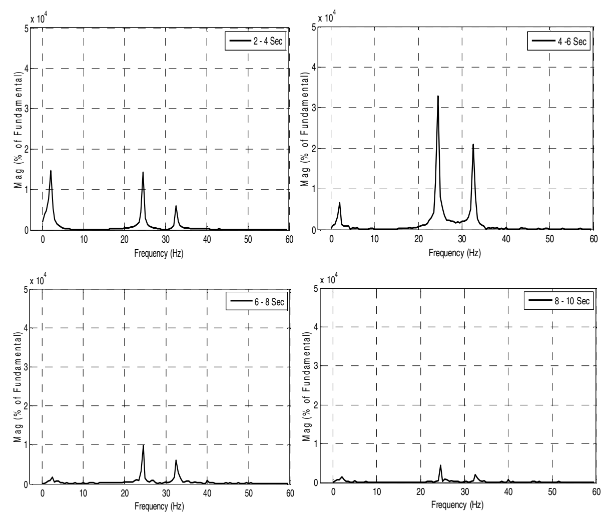

Fig. 11. FFT analysis accelerating power of generator signal (STATCOM with voltage control and with SSDC (K_P=5)).

Also comparing Fig. 11 and Fig. 12, shows that damping rate of mechanical modes (except zero mode), when K_P=6 is bigger than the state which K_P=5. FFT analysis on the accelerating power signal of generator and LP-GEN section torque when the filter is used in SSDC, K_P=6 and STATCOM is working in voltage control mode, is shown in Fig. 13 and Fig. 14. LP-GEN section torque when the filter is used in SSDC, STATCOM is working in var control mode and K_P=6 is shown in Fig. 15. By comparing Fig. 13 and Fig. 15 like previous case, the damping rate when STATCOM is working in var control mode is bigger.

IV. SIGNAL TRANSMITION DELAY

An important aspect with remote signal acquisition is the transmission delay. This is the delay in the transmission of

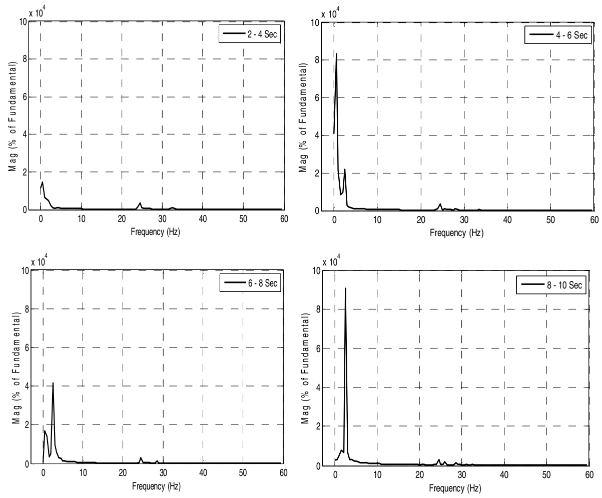

Fig. 12. FFT analysis accelerating power of generator signal (STATCOM with voltage control and with SSDC (without high-pass filter, K_P=6)).

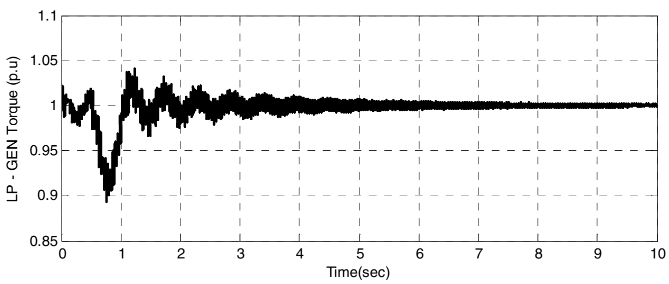

Fig. 13. Variation of LP-GEN section torque for pulse change in input mechanical torque (STATCOM with voltage control and with SSDC (with high-pass filter, K_P=6)).

the acquired signal from the remote site to the location where it is to be used. The typical range of this delay is 20-50 milliseconds [9], [11]. The delayed arrival of the remote signal to the FACTS Controller location may cause system instability. As a result, suitable controllers have been recently designed to compensate the effect of delay in damping inter-area oscillation modes typically in the frequency range 0.1-0.8 Hz [6], [9].

The effect of transmission delay in remote signals is examined for the damping of SSR modes by the STATCOM SSDC. It is found that a 51 milliseconds delay may cause the system to become unstable. The delay is modeled with a transport delay block (Fig. 1).

V. Conclusion

In this paper, the performance of the remote accelerating power signal of generator to damp SSR has been studied. It is found that a subsynchronous damping controller (SSDC) of STATCOM, that is based on remote accelerating power signal of generator, can successfully damp all SSR modes for critical compensation level. The SSDC has a simple structure of a booster and high-pass filter.

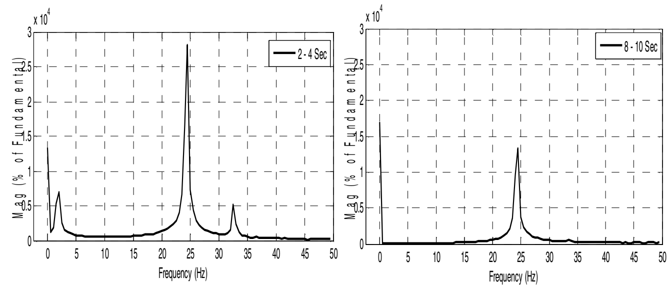

Fig. 14. FFT analysis accelerating power of generator signal (STATCOM with voltage control and with SSDC (with high-pass filter, K_P=6)).

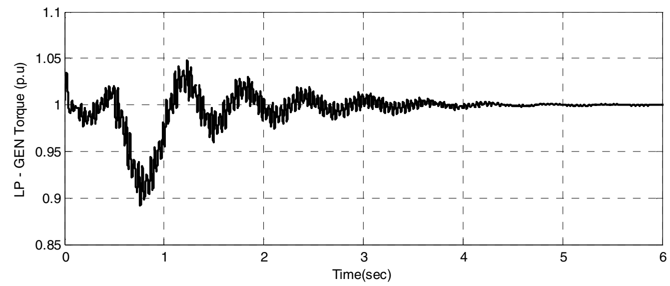

Fig. 15. Variation of LP-GEN section torque for pulse change in input mechanical torque (STATCOM with var control and with SSDC (with high-pass filter, K_P=6)).

VI. Appendix

The parameters of the excitation system including AVR, Power System Stabilizer (PSS) and ±100 MVAr, 500 kV STATCOM are presented in tables I and II.

TABLE I
PARAMETERS OF THE EXCITATION SYSTEM, AVR AND POWER SYSTEM STABILIZER (PSS)

Excitation system and AVR		Power System Stabilizer (PSS)	
Tr	0.010	Sensor time constante	0.03
Ka	150	Gain	6.7
Ta	0.025	Wash-out time constante	1
Ke	1	Lead-lage #1 (*Tnum*)	0.2
Te	0.001	Lead-lage #1 (*Tden*)	0.01
Kf	0.001	Lead-lage #2 (*Tnum*)	3
Tf	0.1	Lead-lage #2 (*Tden*)	5.4
Efmin	-6	*Vsmin*	-0.1
Efmax	6	*Vsmax*	0.1

TABLE II
PARAMETERS OF THE STATCOM CONTROLLER

Voltage regulation gains		Iq regulation gains	
Kp	1	Kp	10
Ki	1000	Ki	80
Vmax	1	*Imax*	80
Vmin	-1	*Imin*	-80

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