IMPROVE SUB-SYNCHRONOUS RESONANCE (SSR) DAMPING USING A STATCOM IN THE TRANSFORMER BUS

H. Khalilinia, *Student Member, IEEE*, and J. Ghaisari, *Member, IEEE*

***Abstract*--** **Sub-Synchronous Resonance (SSR) oscillations in long transmission line brings to failure of the turbine shaft. STATic COMpensator (STATCOM) is a multifunctional FACTS device which its ability depend on its location on transmission line. In this paper, a controller is proposed and designed for STATCOM in transformer bus to damping SSR in all operation points. The controller is designed based on speed deviation damping signal. In addition to SSR damping, STATCOM implemented in the transformer bus can control line active power and other dynamical events such as first swing stability and power oscillations. Eigenvalue analyses and nonlinear simulations in PSCAD/EMTDC software are employed to illustrate the performance of the proposed controller and the STATCOM. Simulation results approve the proposed scheme capability in SSR damping at different level of series compensations of the transmission lines.**

***Index Terms*--** **Sub-Synchronous Resonance (SSR), STATCOM, transformer bus, speed deviation signal.**

I. INTRODUCTION

SERIES capacitors are one of the conventional series compensators in power systems. They are used for compensation of the inductive reactance of the transmission lines. Series capacitors improve the system stability margin; moreover, they control active power flow among parallel transmission lines [1]. Series capacitors, however, may increase the risk of an adverse phenomenon called Sub-Synchronous Resonance (SSR). SSR is an electric power system circumstance in which the electric network exchanges energy with the generator. The frequency of this exchange is below the synchronous frequency [2]. At this situation, the turbine-generator oscillates at a frequency corresponding to the torsional mode frequency. The torsional oscillations may raise and result in the failure of the turbine shaft [3].

So far, several countermeasures for damping of torsional oscillations such as excitation control [4], and FACTS devices include SVC [5]-[7], TCSC [8], UPFC [9], SSSC [10], and STATCOM [11]-[12], were employed in power systems. In [11], a STATCOM was utilized in the generator bus therefore it could not affect the line active power. In [12], a STATCOM was employed in the electrical center of a transmission line and after the series capacitor. Thus it could also effect in the line active power flow. Although the STATCOM is far from the generator and there was no access to any suitable damping signal for SSR.

In this paper, a STATCOM is located at the transformer bus. This location is same as an electrical middle point of the transmission line. In addition, the selected location of the STATCOM is near to the generator and the generator speed deviation is available as a suitable damping signal to improve SSR and torsional oscillations. The STATCOM in this location controls the line active power in addition to improve SSR and other dynamical phenomena such as first swing stability and power oscillations. In this research work, a controller is also proposed to regulate the voltage of the generator bus along with to improve SSR damping using speed deviation feedback signal. The power system is an IEEE first benchmark system [13] which is equipped with a 6-pulse (SPWM) voltage source converter based STATCOM. Eigenvalue analysis carried out to verify the excellent performance of the proposed controller in SSR damping in a wide variation range of the operation point. Time domain simulations using the nonlinear system model are also carried out to demonstrate the effectiveness of the proposed scheme in the transient SSR damping when the system experiences a three-phase fault at its infinite bus.

II. SYSTEM MODELING

A. Power System Model

The IEEE first benchmark system [13] is shown in Fig. 1. It consists of a synchronous generator connected to an infinite bus via a compensated 500 kV transmission line. The transmission line is represented by a resistance, a reactance X_L and a series compensation capacitor, X_C, which its value depends on the compensation level. The mechanical system consists of four-stage steam turbine, the generator and a rotating exciter. The operating points are 0.3 p.u and 0.9 p.u of line active powers in 0.9 power factor.

Each of torsional modes has largest SSR interaction at a certain value of the series compensation X_C. In this paper, the sub-synchronous resonance phenomenon is investigated for the series compensation X_C from 0.01 p.u to 0.53 p.u or 1% to 75% compensation for the transmission line.

Combining the equation of mechanical system,

H. Khalilinia is with the Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran. (E-mail: hamed@ec.iut.ac.ir).

J. Ghaisari is with the Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran. (E-mail: ghaisari@cc.iut.ac.ir).

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generator, exciter system, governor system, and the capacitor compensated transmission line results in a set of 27 eigenvalues. 20 modes are related to the mechanical system, generator, and the capacitor compensated transmission line and 7 modes are associated with the exciter system and the governor system.

The six-mass model of Fig. 1 has five torsional modes in addition to an electromechanical mode (mode 0). Real parts of the eigenvalues corresponding to the various torsional frequencies vary in magnitude and become unstable at different levels of the series compensation as shown in Fig. 2. It can be seen that modes 1, 2, 3 and 4 become unstable at various value of X_C. The corresponding torsional and electrical eigenvalues of the system without STATCOM are listed in Table I in 0.9 p.u active power and two different values of compensation.

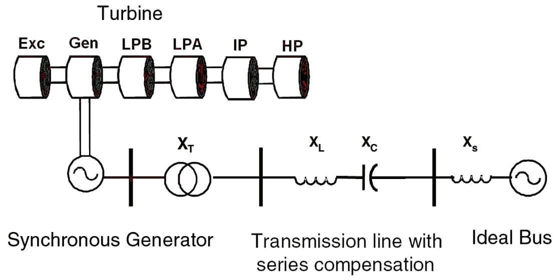


Fig. 1. IEEE First Benchmark Model

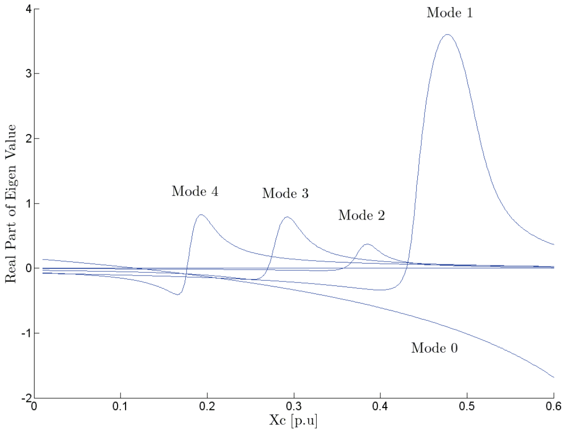


Fig. 2. SSR Modes of First Benchmark Model in 0.9 p.u active power

Fig. 3 demonstrates real parts of the eigenvalues corresponding to the various torsional frequencies at different values of system active power and 60% compensation of the transmission line. Fig. 3 shows that modes 1 and mode 0 have large variation at various value of the active power flow.

TABLE I Eigenvalues analysis of the IEEE first benchmark without STATCOM in 0.9 p.u system active power

Mode	Xc=0.35 *p.u*	Xc=0.42 *p.u*
Torsional 0	-0.46±j10.82	-0.67±j11.78
Torsional 1	-0.27±j99.76	-0.26±j101.09
Torsional 2	-0.02±j127.20	0.12±j126.92
Torsional 3	0.2±j160.45	0.08±j160.50
Torsional 4	0.09±j202.89	0.06±j202.90
Torsional 5	+0±j298.18	+0±j298.18
electrical	-5.40±j137.16	-4.94±j113.17

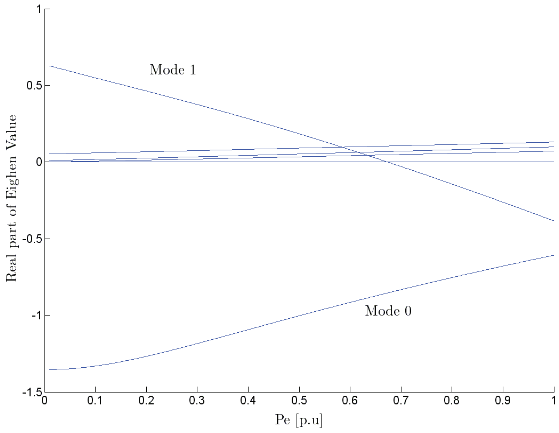


Fig. 3. SSR Mode of First Benchmark Model in 60% compensation

B. STATCOM Model

A single line diagram of the IEEE first benchmark model equipped with a STATCOM connect at the transformer terminal is shown in Fig. 4. The STATCOM consists of a GTO-based 6-pulse (SPWM) voltage source converter and a capacitor (C_S) on the DC side. It is connected to the terminal through a coupling transformer represented by a leakage inductance (L_S) and a resistance (R_S).

If harmonics are neglected, STATCOM is represented in d-q reference frame as:

$$\begin{aligned}
\frac{di_{sd}}{dt} &= -\frac{R_s\omega_B}{X_s} i_{sd} + \omega_B i_{sq} + \frac{\omega_B}{X_s}[V_{sd} - V_{sd}^i] \\
\frac{di_{sq}}{dt} &= -\omega_B i_{sd} - \frac{R_s\omega_B}{X_s} i_{sq} + \frac{\omega_B}{X_s}[V_{sq} - V_{sq}^i] \\
\frac{dV_{dc}}{dt} &= \frac{K\omega_B}{b_c}\sin(\theta_s + \alpha) i_{sd} + \frac{K\omega_B}{b_c}\cos(\theta_s + \alpha) i_{sq} - (\frac{\omega_B}{b_c R_p}) V_{dc}
\end{aligned} \tag{1}$$

Where, K is modulation index which is constant in indirect STATCOM voltage control, and α is the angle between the converter output voltage and the fundamental frequency of the bus voltage. In (1), i_{sd} and i_{sq} are *d*-axis, and *q*-axis components of STATCOM injected current, respectively. The components of the STATCOM output voltage corresponding to *d* and *q* axes are given by:

$$V_{sd}^{i} = KV_{dc}\sin(\theta_s + \alpha)$$
$$V_{sq}^{i} = KV_{dc}\cos(\theta_s + \alpha) \qquad (2)$$
$$V_{s}^{i} = \sqrt{(V_{sd}^{i})^2 + (V_{sq}^{i})^2}$$

θ_s is obtained by:

$$\theta_s = \tan^{-1}\frac{V_{sd}}{V_{sq}} \qquad (3)$$

In (3), V_{sd} and V_{sq} are *d*-axis, and *q*-axis components of the transformer bus voltage respectively.

In this research work, STATCOM is used to damp sub-synchronous resonance significantly as well as to regulate the bus voltage at the connection bus.

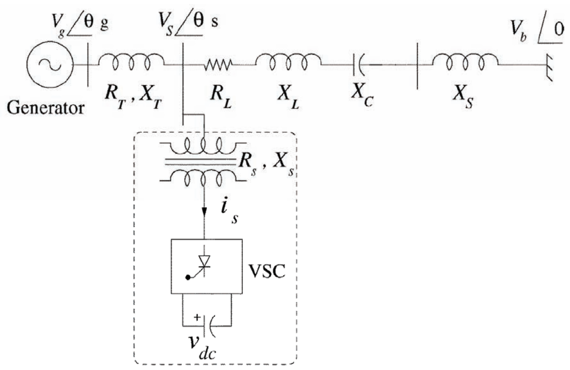


Fig. 4 The Power System using the a STATCOM

III. STATCOM CONTROL STRATEGY

The block diagram of the proposed control system for the STATCOM is shown in Fig. 5. The control system consists of two outer loops, and an internal loop. It uses three feedback signals include the bus voltage, the STATCOM reactive current and rotor the angular speed deviation.

Fig.6. demonstrates the real part of torsional mode of the IEEE first benchmark with STATCOM when it is controlled by a voltage control loop without damping signal. It can be seen that, if STATCOM only utilizes the voltage control loop, it cannot provide suitable damping for SSR phenomena.

Also, STATCOM without suitable damping signal make torsional modes more unstable at low percent compensation of the transmission line.

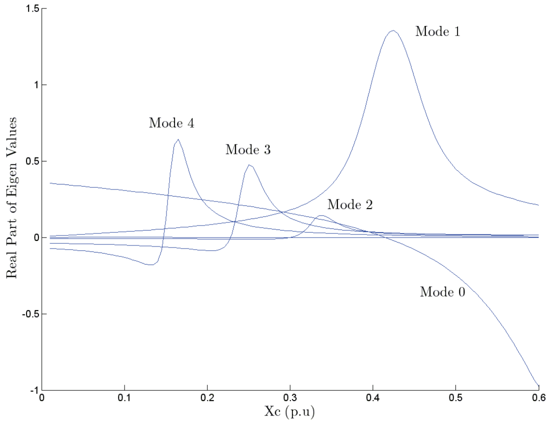


Fig. 6 SSR Mode of First Benchmark Model in 0.9 p.u active power with STATCOM in transformer bus without damping signal

The rotor angular speed deviation is an alternative stabilizing signal [7]. The angular speed of the rotor contains components for all turbine modes. Consequently, if the angular speed deviation is used in the STATCOM control system, all torsional modes in addition to the mode corresponding to the generator mass will be affected [7].

Fig.7 and Fig. 8 demonstrate the real parts of torsional modes of the IEEE first benchmark with STATCOM in transformer bus when it is controlled by a voltage control loop using angular speed deviation feedback for damping signal in two different value of line active power.

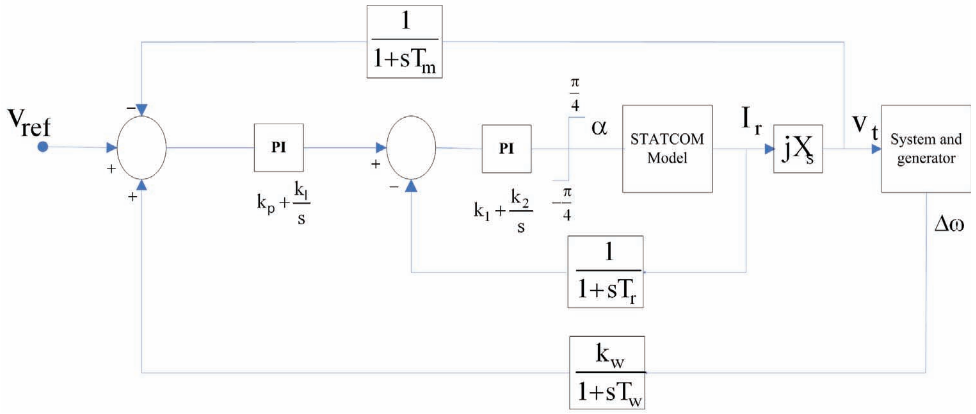


Fig.5. Proposed control system scheme

It can be seen that, if STATCOM utilizes the speed deviation as a damping signal, it provides suitable damping for SSR phenomena in all percent of compensation and entire operation point. To increase the damping ratio and to remove small magnitude oscillations in a relatively short time an internal reactive current loop is added to the STATCOM control system.

Table II illustrates the torsional and electrical modes of the power system with damping signal for two different values of compensation. Comparing table II and table I is shown that electrical mode frequency reduce in presence of STATCOM and proposed controller.

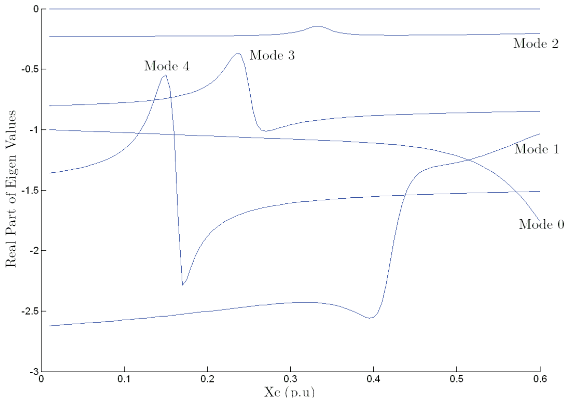


Fig.7 SSR Modes of First Benchmark Model in 0.9 p.u active power using STATCOM in transformer bus

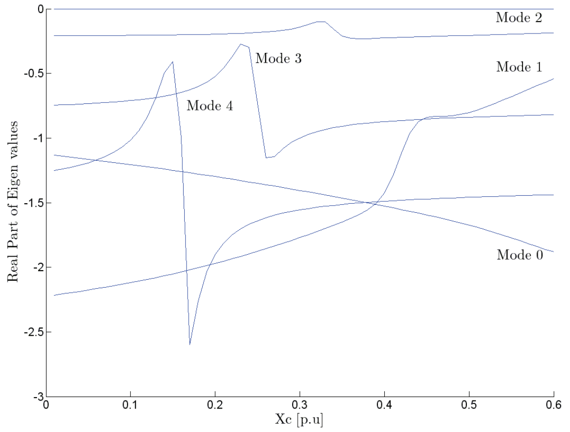


Fig.8 SSR Modes of First Benchmark Model in 0.3 p.u active power using STATCOM in transformer bus

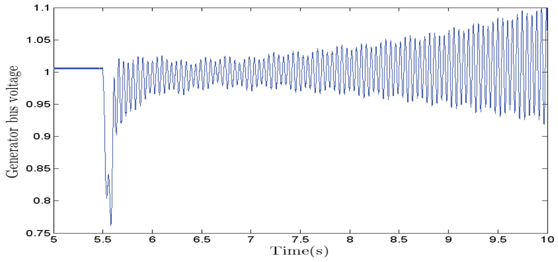
TABLE II Eigenvalues analysis of the IEEE first benchmark with STATCOM in the transformer bus.

Mode	Xc=0.35 *p.u*	Xc=0.42 *p.u*
Torsional 0	-1.09±j11.10	-1.37±j11.61
Torsional 1	-2.44±j98.41	-3.60±j96.29
Torsional 2	-0.18±j126.96	-0.35±126.83
Torsional 3	-0.90±j160.68	-1.68±j160.61
Torsional 4	-1.57±j203.22	-2.72±j203.33
Torsional 5	-0±j298.17	-0±j298.18
electrical	-6.72±j121.86	-6.84±j100.62

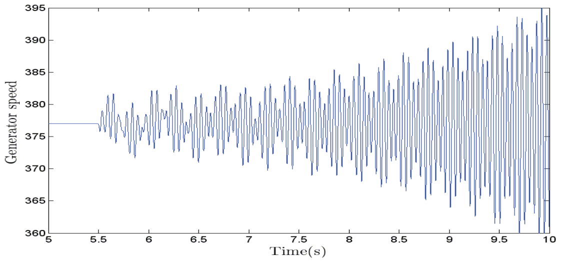
Comparing table I with table II approves that the real part of mode 0 which illustrates the power oscillation dynamic or POD mode, reduces significantly when the STATCOM and its damping controller is used in transformer bus.

IV. NONLINEAR SIMULATION RESULTS

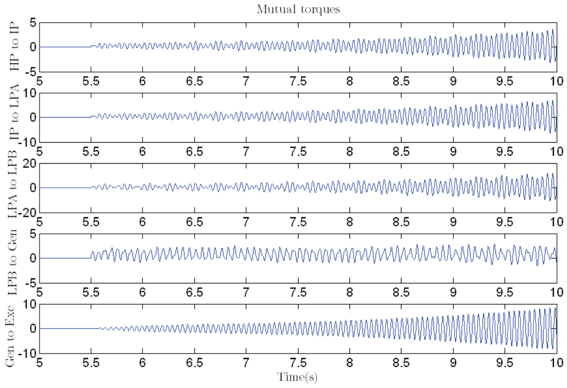
In this section the transient simulations of the nonlinear power system equipped with a STATCOM are carried out using PSCAD/EMTDC. The simulation results are obtained when a three-phase fault at the infinitive bus is occurred. The three-phase fault is initiated at t=5.5 second, and the fault duration is 4.5 cycle (75 ms).



a) Bus voltage of the generator terminal (p.u)



b) Rotor angular speed of the generator (rad/s)



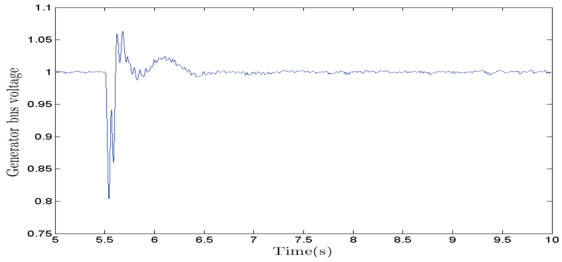
c) Mutual torques between masses of turbine-generator

Fig 9. Nonlinear simulation results of IEEE First Benchmark without STATCOM.

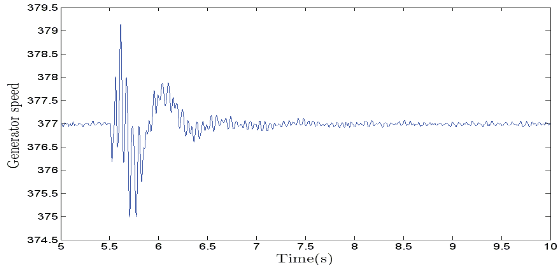
To show the superior performance of the proposed damping control system, simulations are repeated in three stages. First, IEEE First benchmark is only used. In the second stage, STATCAM with proposed controller add to transformer bus in 0.9 p.u line active power and 60% compensation of the transmission line. And then, simulation has been carried out in 0.3 p.u line active power and 60% compensation of the transmission line. The simulation results for each case are obtained and plotted in Figs. 9-11.

Fig. 9 show the voltage terminal and rotor angular speed of the generator as well as the mutual torques between the masses of turbine-generator model, when the IEEE first benchmark is used alone. It can be seen that the unstable modes cause instability in presence of SSR.

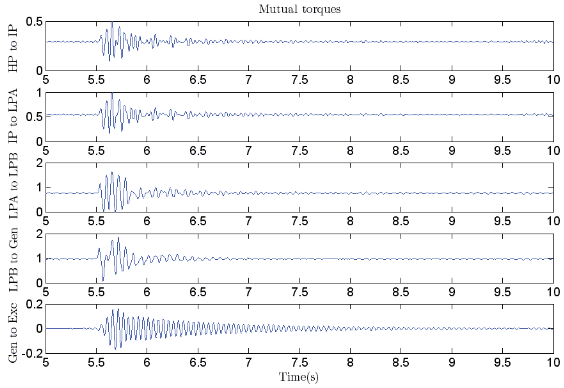
Fig. 10 and Fig. 11 show the results when a STATCOM with proposed controller add to transformer bus in 0.9 p.u and 0.3 p.u line active power with 60% compensation of the transmission line. The simulation results illustrate the effective improvement in SSR damping.



a) Bus voltage of generator terminal (p.u)



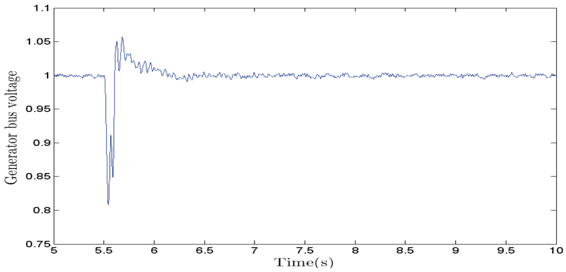
b) Rotor angular speed of the generator (rad/s)



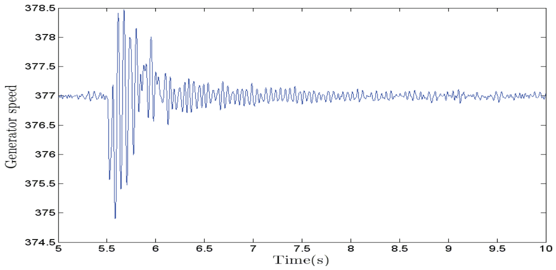
c) Mutual torques between masses of turbine-generator

Fig. 10. Simulation results when STATCOM use in transformer bus in 0.9 p.u system active power and 60% compensation of the transmission line.

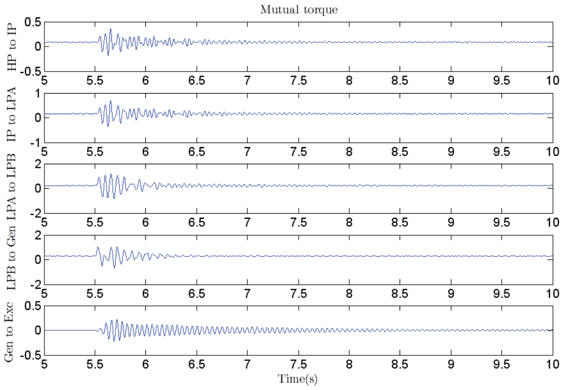
The nonlinear simulation results approve, STATCOM in the transformer bus with proposed controller not only removes the steady state SSR completely and quickly but also remove transient SSR from shaft successfully in all operation point.



a) Bus voltage of generator terminal (p.u)



b) Rotor angular speed of the generator (rad/s)



c) Mutual torques between masses of turbine-generator

Fig. 11. Simulation results when STATCOM use in transformer bus in 0.3 p.u system active power and 60% compensation of the transmission line.

V. CONCLUSION

In this paper, a controller is proposed and designed for STATCOM in transformer bus to damping SSR. This location is same as an electrical middle point of the transmission line. It is shown that the STATCOM in the selected location damps SSR successfully in addition to control the line active power and damping power oscillations. Eigenvalues analyses as well as nonlinear simulations in a PSCAD/EMTDC environment are carried out. The results verify that the STATCOM using the proposed controller using generator speed deviation feedback damps SSR fast and completely in the wide variations range of operating points.

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Biography

Hamed Khalilinia was born in Tehran, Iran, in 1984. He received his B.Sc. degree from the Department of Electrical and Computer Engineering, Shahid Rejaee University, Tehran, Iran, in 2006. Now, He is a master student in Electrical Engineering at Isfahan University of Technology. His research interests include dynamic and stability of power systems, and FACTS devices.

Jafar Ghaisari received his B.Sc., M.Sc., and Ph.D. degrees with honors in Electrical Engineering from Isfahan University of Technology (IUT), Iran, in 1996, 1999, and 2006 respectively. During the Ph.D. program, he joined the Department of Electrical and Computer Engineering, Queen's University, Canada, as a visiting researcher from 2004 to 2005, and received research scholarships. Since Dec. 2006, He has been with the Department of Electrical and Computer Engineering at Isfahan University of Technology, Iran. His current research interests include control systems, and control applications in FACTS devices and power electronics.