A Novel Approach for Damping Subsynchronous Resonance Using a STATCOM

D. Rai, G. Ramakrishna, S.O. Faried, and A. Edris

Abstract— **This paper investigates the impact of a STATCOM operating in a phase imbalanced mode on damping subsynchronous resonance in series capacitive compensated transmission grid. Phase imbalance has the potential of reducing the energy exchange between the electrical and mechanical sides of turbine-generator and, therefore, damps the subsynchronous oscillations resulting from series capacitive compensation.**

The effectiveness of the proposed scheme is demonstrated on the IEEE first benchmark model by means of time domain simulations using the EMTP-RV program.

Index Terms—**Subsynchronous resonance, FACTS, voltage sourced converter.**

I. INTRODUCTION

SERIES capacitive compensation is a very useful way for increasing the transmission capacity and improving transient stability of the transmission system. However, one problem associated with it is the risk of Subsynchronous Resonance (SSR) [1]. Therefore, overcoming such a problem has been an active area of research [2].

Flexible AC Transmission System (FACTS) technology provides a mechanism for controlling transmission grids and for increasing the transmission capacity [3-5]. FACTS controllers have the flexibility of controlling both real and reactive power, which in addition to this control could provide an excellent tool for improving power system dynamics. Several studies have investigated the potential of using this capability in mitigating Subsynchronous Resonance (SSR) of series capacitive compensated transmission grids [6-11]. Balanced operation of TCSC, STATCOM, and SSSC have been implemented and/or studied as means for damping SSR.

An effective SSR countermeasure based on creating phase imbalance was introduced in [12-14]. The idea behind phase imbalance is to weaken the electromechanical coupling which will result in reduction of the energy exchange between the electrical and mechanical sides of turbine generators.

This paper investigates the capability of STATCOM when operated in phase imbalance mode in mitigating and/or reducing SSR. This approach is based on using the STATCOM for injecting unbalanced reactive currents during system disturbances. The validity and effectiveness of the proposed scheme have been demonstrated on the IEEE first benchmark model by means of time simulation analysis using the EMTP-RV program.

II. POWER SYSTEM CONFIGURATION USED FOR THE STUDY

To demonstrate the validity of the proposed scheme, the IEEE first benchmark model (FBM) for computer simulation of SSR, shown in Fig. 1, is adopted as a test system [15], where Z_T is the transformer impedance, $Z_{TL} = R_{TL} + X_{TL}$ is the transmission line impedance, C is the series compensating capacitor, Z_F is the fault impedance and Z_{sys} is the infinite bus short circuit impedance. For the time domain simulation studies, the synchronous generator is represented in the *d-q-o* reference frame. The turbine-generator mechanical system is represented by a linear multi-mass-spring dashpot system. The transmission line is modeled for the present study as a transposed non-coupled parameters line using series impedance representation. The infinite bus is represented simply as a constant amplitude sinusoidal voltage at synchronous frequency. Circuit-breakers are represented as ideal switches which can open at current zero crossings. The dynamics of the governor system of the turbine-generator set are neglected and the input mechanical torque is assumed to remain constant corresponding to the steady-state operating conditions. The dynamics of the turbine-generator excitation system are included in the simulation model.

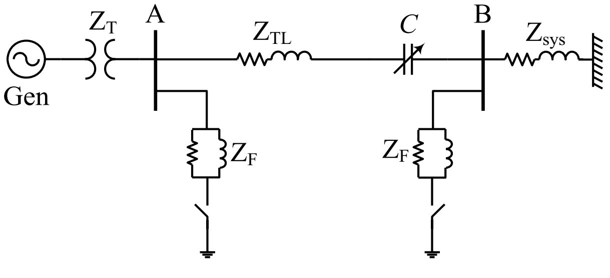

Fig. 1. Schematic diagram of the test system.

Fig. 2 shows the EMTP-RV simulation time responses of the turbine-generator electrical power and shaft torsional torques during and after clearing a 4.5 cycle three-phase fault

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Manuscript received October 4, 2008.

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at bus B. The compensation level is defined as X_C/X_{TL} and is assumed to be 57.4%. The system operating condition corresponds to 0.89 + *j* 0.06 per unit power delivered to the infinite bus system at 1.0 per unit bus voltage. As it can be seen from Fig. 2, first one second transient oscillations following the fault clearing are due to fault, and after two seconds onwards, the shaft torsional torques exhibit severe amplifications due to SSR. This case is adapted throughout the paper as the reference case for comparison.

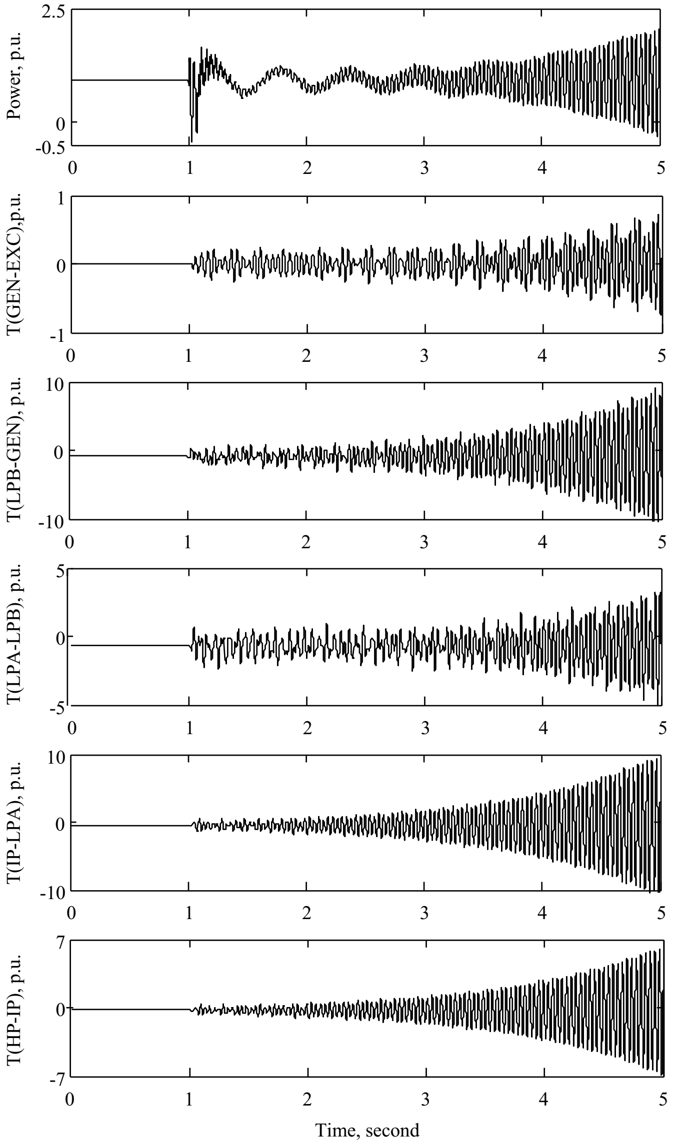

Fig. 2. Turbine-generator electrical power and shaft torsional torques during and after clearing a 4.5-cycle, three-phase fault at bus B (compensation level = 57.4%).

III. STATCOM MODELING

STATCOM is a shunt connected solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals [5]. A STATCOM is modeled using a GTO based three-level Sinusoidal Pulse Width Modulation converter. The GTO switches are modeled as ideal switches that can be turned *on* and *off* by a control signal obtained from the controller. The schematic diagram of STATCOM is shown in Fig. 3. The power electronic circuit is coupled to the high voltage ac system via a coupling transformer.

The controller takes inputs signals (e.g. DC capacitor reference voltage and desired output voltage levels) and the system variables (e.g. current and voltage) and generates the required gate signals. An *LC* filter is used to filter out the switching frequency noises. The technical details of the STATCOM are given in Table A.I.

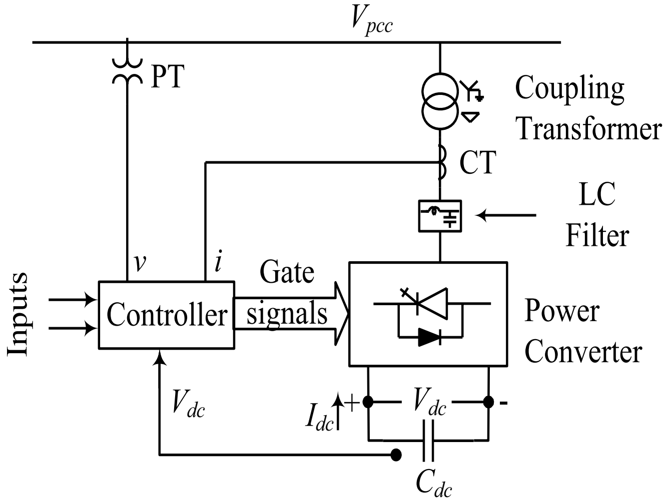

Fig. 3. A STATCOM implementation block diagram.

IV. STATCOM IMBALANCE MODE OF OPERATION

The STATCOM unbalanced mode of operation is achieved by controlling the positive and negative sequence components of the reference voltage in the STATCOM control circuitry using a voltage regulator which is built upon sequence component theory [16]. This regulator uses two separate control loops to control independently the positive and negative sequence voltages to their desired values. To achieve this, the instantaneous values of the three-phase voltages are transformed into the synchronous reference frame. In such a frame, the regulated values appear as dc rather than 60 Hz ac. This makes it much easier to control these regulated values in the steady-state driving the errors to almost zero.

When the phase values are unbalanced, the traditional synchronous frame transformation produces an output that contains a second harmonics component in addition to a dc component. The positive sequence component is no longer clearly indicated because of the loss of three-phase symmetry in the input quantities. To eliminate the need for three-phase symmetry, a single-phase synchronous frame transformation is used. This transform projects each phase voltage onto an orthogonal synchronous reference frame. The synchronous frame phase voltages are then later combined to obtain the sequence components. The block diagram of the synchronous frame transformation is shown in Fig. 4 and the detailed

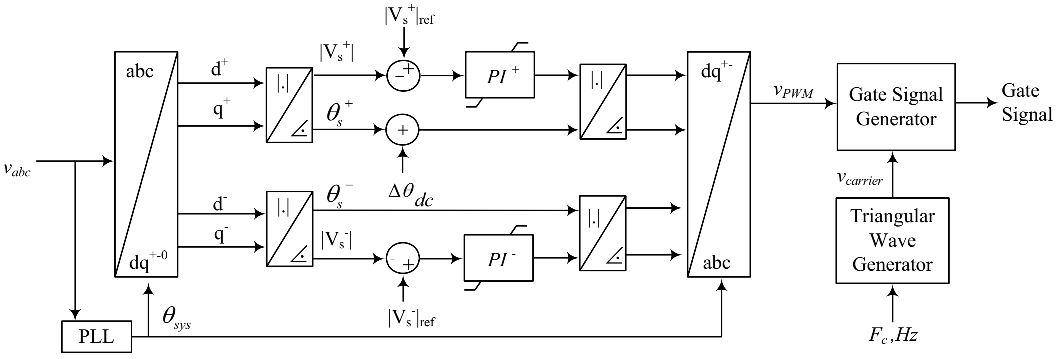

Fig. 4. STATCOM voltage regulator for controlling the positive and negative sequence components.

equations of the transformation are given in [16].

The three-phase bus voltage is measured and passed to a *abc* to dq^{+-0} synchronous frame transformation block which separates it into its positive and negative sequence components. For each sequence component, separate regulation loops are applied to the magnitude and the phase angle. The magnitudes of the positive and negative sequence components are compared to their corresponding reference values producing error signals which are fed into their corresponding PI controllers. The unbalanced values for the bus voltages are selected within ±5% of the rated value and the positive and negative sequence reference voltage components are back calculated from those values. A more detailed discussion is provided later in Section V. The phase angle of the inverter positive sequence voltage is used to control the DC capacitor voltage through the DC capacitor voltage controller shown in Fig. 5. The output of this controller, $\Delta\theta_{dc}$ is added to the positive sequence phase angle. At steady-state, the inverter voltage lags the line voltage by a small angle in order to charge the capacitor and supply the incurred losses in magnetic and switching circuits. The outputs of the two PI controllers (PI^+ and PI^-) are then converted back into phase quantities using a dq^{+-0} to *abc* synchronous frame transformation block. The resultant phase quantities are used as reference signals for the PWM converter.

The neutral point potential of three-level converter is balanced by bypassing the three-level modulation of that phase, which will contribute further to the imbalance, to traditional two-level modulation. Since only one phase is modulated using the two-level PWM, there is not a significant reduction in the effective switching frequency [17].

V. SIMULATION RESULTS

The time domain simulations of FBM model with a STATCOM placed at a fractional distance *M* of the length of the transmission line from bus A, as shown in Fig. 6, are performed using the EMTP-RV program. The transmission line operating condition and compensation level are same as the reference case given in Section II. A three-phase to ground fault is applied at bus B at t = 1 sec for 4.5 cycle. The STATCOM is operated in an unbalanced mode just after clearing the fault for a short duration (which is typically 4 to 5 seconds in the studies performed). The STATCOM bus voltage (v_a, v_b, v_c) were controlled between ±5% of 1 p.u. Then several time domain simulations were carried out to find out a minimum value for the unbalance that will effectively damp out all the SSR oscillations. Using a small voltage deviation of Δv = 0.01 p.u., a set of 100 unbalanced voltage combinations were obtained. Some of the simulation results from these studied are presented below.

Fig. 7 shows the dc capacitor voltage and the unbalanced bus voltages, and Fig. 8 shows the turbine-generator electrical power and shaft torsional torques plots for the STATCOM at bus A, i.e. M = 0. The comparison between Fig. 8 and the reference case (Fig. 2) shows that the operation of the STATCOM in a phase imbalance mode effectively damps the SSR oscillations.

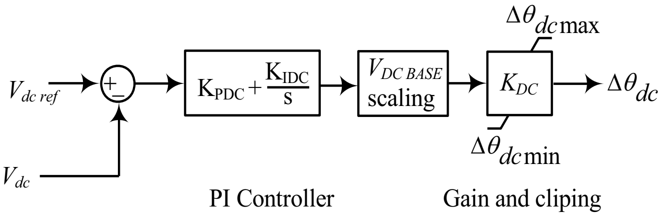

Fig. 5. The DC capacitor voltage controller.

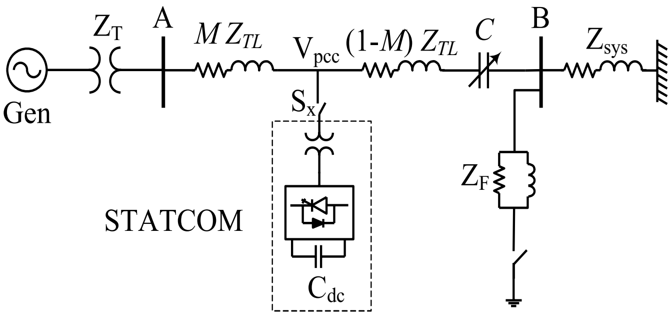

Fig. 6. A schematic diagram of the test system with a STATCOM for EMTP – RV simulation.

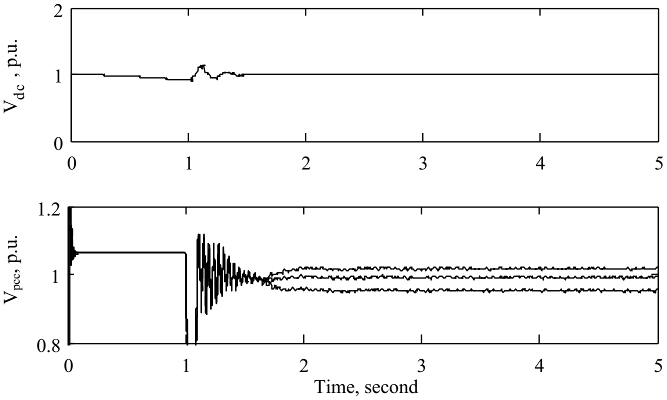

Fig. 7. STATCOM bus and dc capacitor voltages after clearing a 4.5-cycle, three-phase fault at bus B (compensation level = 57.4%, STATCOM is employed at bus A: $v_a = 0.99$ p.u., $v_b = 1.01$ p.u., $v_c = 0.97$ p.u., $M = 0$).

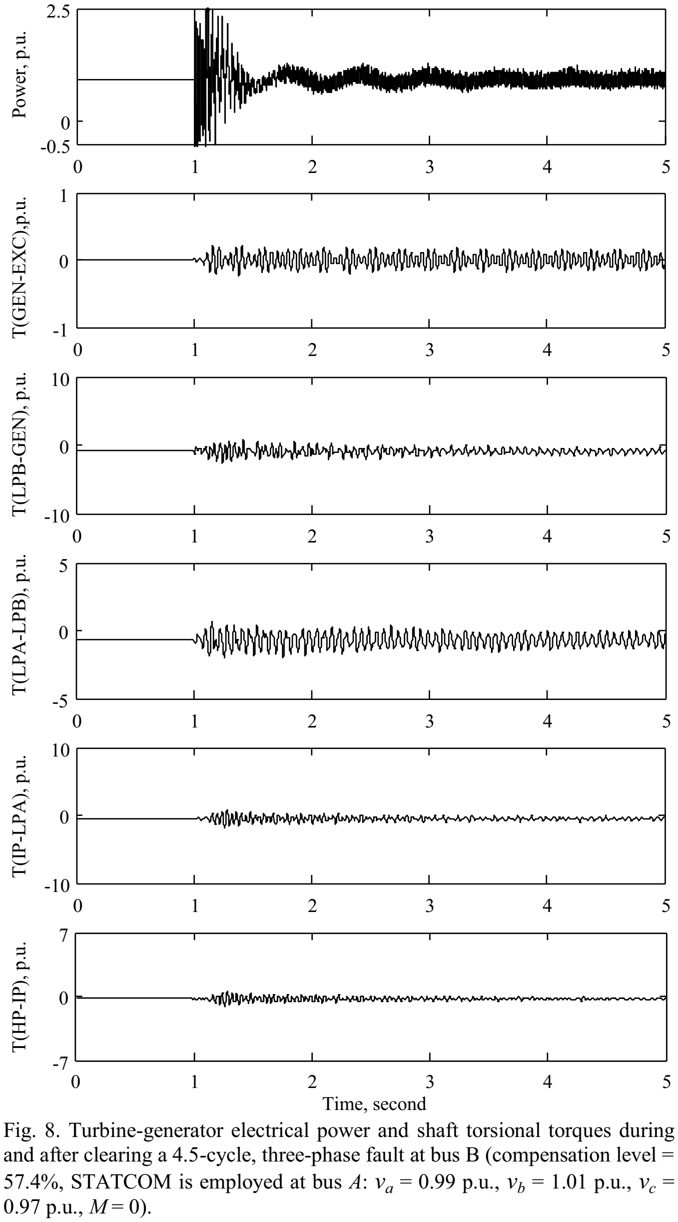

Fig. 8. Turbine-generator electrical power and shaft torsional torques during and after clearing a 4.5-cycle, three-phase fault at bus B (compensation level = 57.4%, STATCOM is employed at bus A: $v_a = 0.99$ p.u., $v_b = 1.01$ p.u., $v_c = 0.97$ p.u., $M = 0$).

The impact of the STATCOM location on its torsional damping effect is investigated by changing the fractional distance M. The turbine-generator electrical power and shaft torsional torques for M equal 0.1 and 0.15 are shown respectively in Figs. 9 and 10. As it can be seen from these figures, the STATCOM at these two locations effectively damp all the shaft torsional torques. The ability of the STATCOM to damp the SSR oscillations starts, however, to decrease as M increases beyond 0.18. Fig. 11 shows the turbine-generator electrical power and shaft torsional torques for $M = 0.20$. As it can be seen from this figure, at this location, the STATCOM torsional damping effect is noticeably reduced and it cannot effectively damp the (GEN-EXC) shaft torsional torque. The controller parameters were found by performing several time domain simulations for the different operating conditions and an optimum values was found from there which could good results for all the operating conditions. More details on tuning of the PI parameters can be found in [18]. The controller gains for the above cases are given in Table A.II.

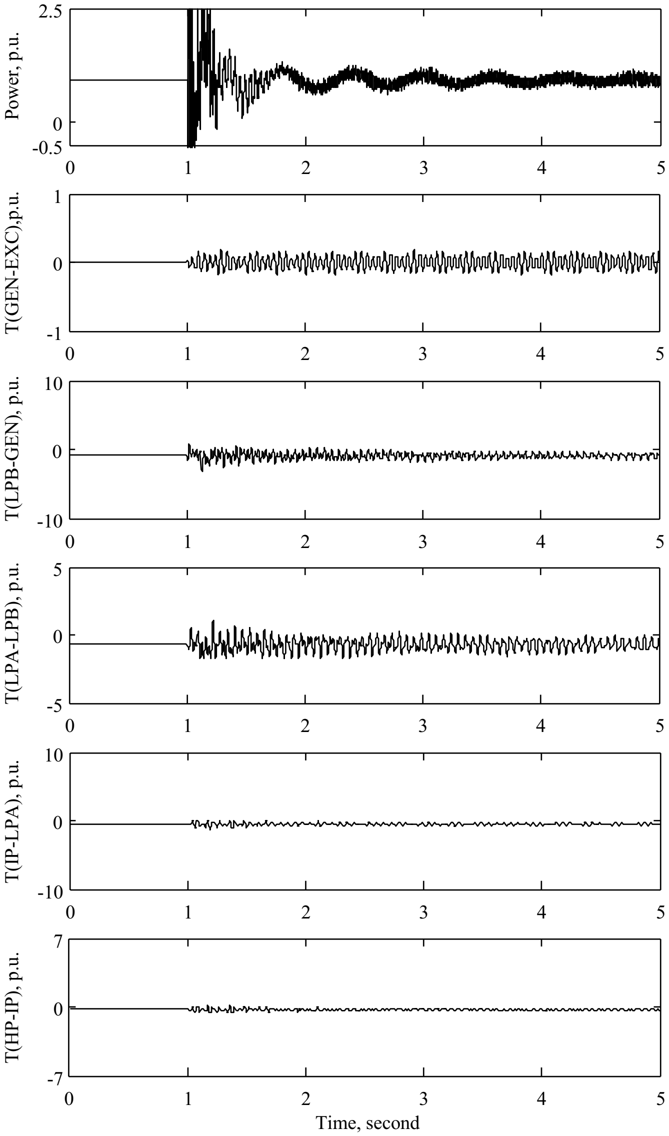

Fig. 9. Turbine-generator electrical power and shaft torsional torques during and after clearing a 4.5-cycle, three-phase fault at bus B (compensation level = 57.4%, STATCOM is employed: va = 0.99 p.u., vb = 1.01 p.u., vc = 0.97 p.u., M = 0.10).

VI. CONCLUSION

The paper introduced the use of the phase imbalance concept in STATCOM as a mean to mitigate the Subsynchronous Resonance oscillations in series capacitor compensated power systems. The effectiveness of the proposed schemes in damping SSR is demonstrated using digital computer simulations on the IEEE first benchmark model.

As in any dynamical system investigations, the results can be influenced by a number of factors, such as system configurations, system parameters and STATCOM ratings. Thus, the conclusions presented are related to the specific problems studied. Further studies are presently going on aimed at applying the schemes to a real compensated power system and to develop practical basis for the choice of the most suitable parameter values of the scheme.

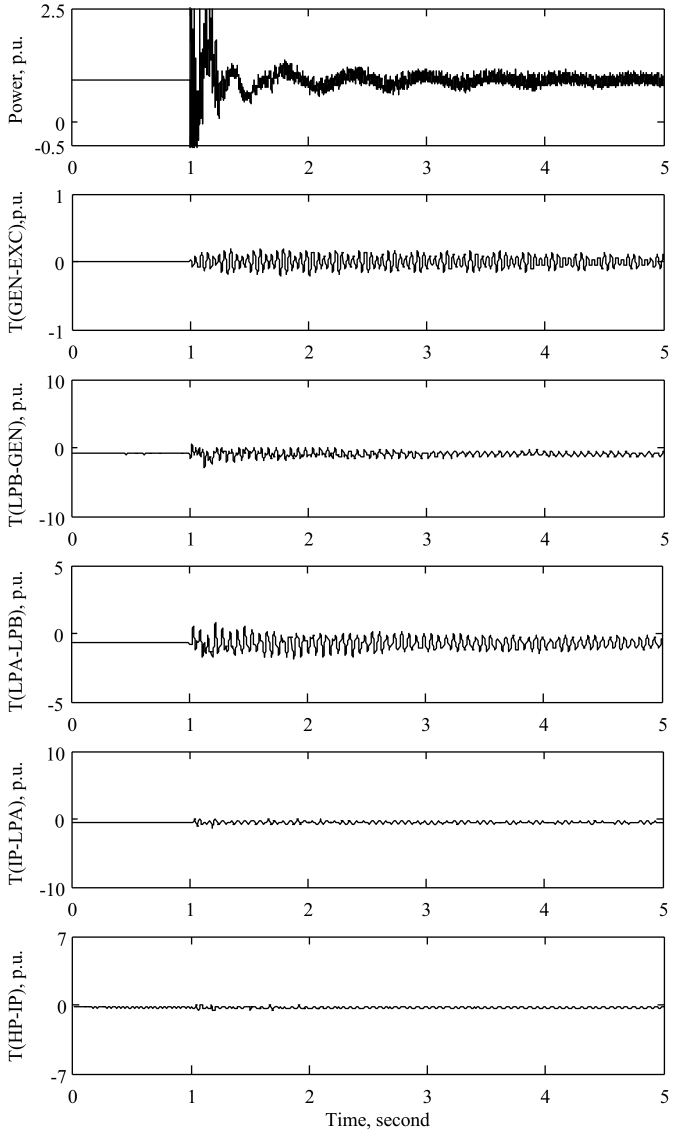

Fig. 10. Turbine-generator electrical power and shaft torsional torques during and after clearing a 4.5-cycle, three-phase fault at bus B (compensation level = 57.4%, STATCOM is employed: v_a = 0.99 p.u., v_b = 1.01 p.u., v_c = 0.97 p.u., M = 0.15).

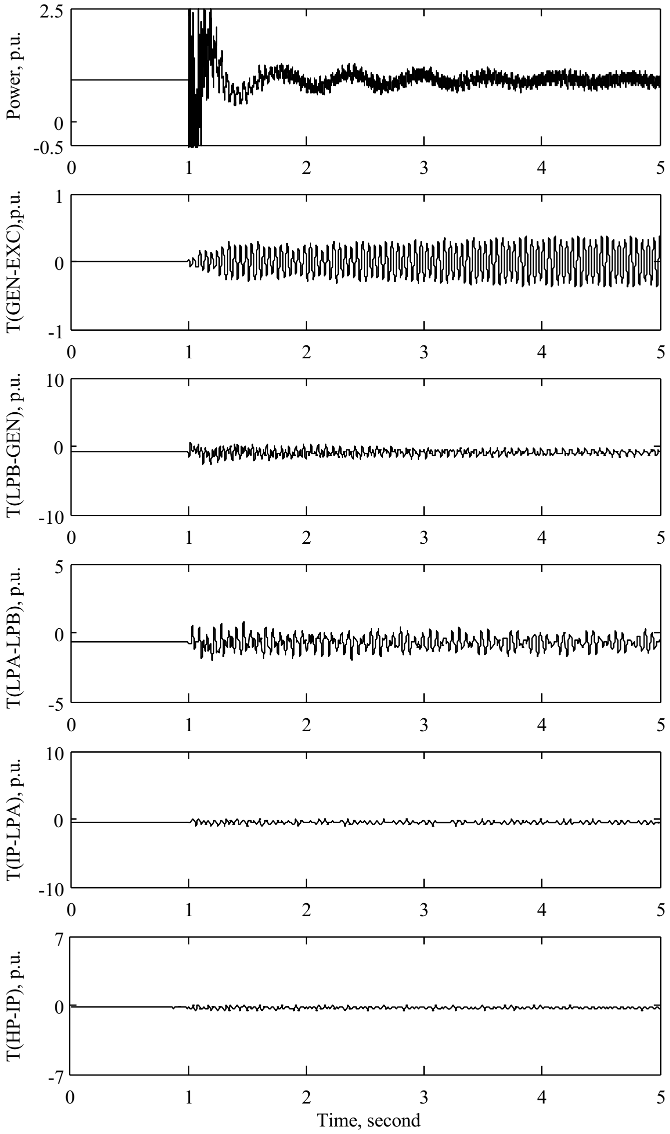

Fig. 11. Turbine-generator electrical power and shaft torsional torques during and after clearing a 4.5-cycle, three-phase fault at bus B (compensation level = 57.4%, STATCOM is employed: v_a = 0.99 p.u., v_b = 1.01 p.u., v_c = 0.97 p.u., M = 0.20).

APPENDIX A

The STATCOM parameters are given in Table A.I and the controller gains are given in Table A.II.

TABLE A. I
STATCOM PARAMETERS

Coupling transformer	$V_1/V_2 = 500/13.2\ kV$	
	$x_t = 0.1\ p.u.$	$r_t = 0.005\ p.u.$
Converter type	Three level SPWM	
LC Filter	$L = 0.09\ mH$	$C = 0.09\ mF$
DC side voltage	$28\ kV$	
Carrier frequency	$f_c = 1980\ Hz$	

TABLE A. II
PI CONTROLLER PARAMETERS FOR STATCOM CASE STUDIES

Cases	Positive/Negative sequence	DC voltage
Fig. 8	$K_P^+ = 1$, $K_I^+ = 50$ $K_P^- = 0.05$, $K_I^- = 30$	$K_{PDC} = 1.5$, $K_{IDC} = 150$ $K_{DC} = 0.2$
Figs. 9, 10, 11	$K_P^+ = 1$, $K_I^+ = 50$ $K_P^- = 0.1$, $K_I^- = 60$	$K_{PDC} = 2$, $K_{IDC} = 150$ $K_{DC} = 0.2$

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