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SUBSYNCHRONOUS TORSIONAL OSCILLATIONS AND RESONANCE MITIGATION IN HVDC SYSTEM AND STATCOM COMBINATION

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Abstract- This paper demonstrates the ability of HVDC system and STATCOM as a member of FACTS device to mitigate the unfavorable Subsynchronous Torsional Oscillations (SSTO) and Subsynchronous Resonance (SSR). Two auxiliary controllers are designed and granted to the conventional controllers of each device. It is the first time that the capability of damping controllers are clarified for both SSR and SSTO. Fast Fourier Transform is implemented to analyze the results. Time domain simulation in Matlab/Simulink is carried out on IEEE Second Benchmark Model (SBM) aggregated with HVDC system and STATCOM to prove the effectiveness of the proposed controllers. A comparison between HVDC and STATCOM in SSR attenuation is also investigated. The results prove the exceptional performance of both STATCOM and HVDC when they operate cooperatively.

Keywords: HVDC, Sub-Synchronous Torsional Oscillations (SSTO), STATCOM, Sub-Synchronous Resonance (SSR), FACTS device.

I. INTRODUCTION

High Voltage Direct Current (HVDC) system obtains the DC current from High Voltage Alternative Current (HVAC) through the use of HVDC converters and their associated devices like filters, reactors and capacitor banks which provide the reactive power for the HVDC converters. Study of HVDC transmission system characteristics and behavior, will be necessary because it is one of the most dependable ways of transferring power. For long distance overload transmission systems (more than 600 km), binding between two asynchronous power systems and under water or underground transmissions (more than 50 km), the HVDC systems are economically more beneficial than HVAC transmission systems [1].

Large HVDC systems now exist in entire world. These include the pacific intertie which has a total capacity of 3100MW over a distance of 1360 km and the Hydro Quebec New England link has a capacity of 225MW. Itaipu in Brazil has an HVDC scheme of 6300MW, the cross channel UK- France scheme has a capacity of 2000MW, Wybord in Russia has a capacity of 1050MW. AS to 2005, the worldwide installed HVDC capacity was 55GW which was 1.4% of the worldwide installed generation capacity [2, 3]. Due to some certain conditions in the HVDC transmission system, the torsional oscillations in the sub-synchronous frequency can be enticed in presence of interaction between HVDC controllers and turbine generator shaft.

The first report with regard to adverse phenomenon of sub-synchronous torsional oscillations (SSTO) due to the interaction between the turbine-generator units and the HVDC system, was in 1977 at Square Butte project in North Dakota [4]. The tests in this case showed that the rectifier current control loop and the Frequency Sensitive Power Control (FSPC) that was designed to damp oscillations can cause instability of the 11.5Hz torsional mode. The damping for this torsional oscillation was improved by an adjustment to the transfer function of the rectifier current control loop and the incorporation of a 11.5 Hz notch filter into the FSPC [5].

Torsional mode oscillations of a turbine-generator system produce a slight modulation of the speed of the generator that cause phase and amplitude modification of the voltage waveform. Variation in the terminal voltage of the machine can cause DC side voltage and current variation which can cause the response of the closed-loop current control and this will produce a change in the electrical torque of the machine [6, 17]. The most effective solution to this adverse alternation is to carefully design the controls of the connected system to eliminate the sub-synchronous torsional interactions problem.

The significant problem in High Voltage Alternating Current (HVAC) transmission system is sub-synchronous resonance (SSR). SSR is an adverse phenomenon which occurs in transmission lines that are compensated with Series capacitors. However, the series capacitors coupled with line reactance, may trigger oscillatory modes inherent in the mass-spring system of turbine generators, resulting in SSR [7]. The consequences of SSR phenomenon and SSTO can be dangerous, because they can deteriorate the stability of torsional and mechanical modes on the shaft of a turbine-generator system. The turbine-generator shaft will be broken with torsional oscillations due to these phenomena [8].

The main focus of this paper is to present a systematic approach for designing of a supplementary controller for damping SSTO and SSR. The supplementary Subsynchronous Oscillations Damping Controller (SSODC) is employed first at the rectifier end of an HVDC link connected in parallel with the AC line to suppress the both SSTO and SSR. In the next part, the STATCOM as a member of Flexible AC Transmission System (FACTS) device that is connected at the middle of the AC transmission line is implemented to study SSTO and SSR phenomenon. A new auxiliary damping signal for STATCOM (ADSS) designated as Computed Internal Angle (CIA), is also proposed because the STATCOM with its conventional voltage controller is not capable of mitigating SSR or SSTO. Eventually, comprehensive comparison of ADSS and SSODC is investigated to prove the superior performance of each controller in SSR and SSTO alleviation.

II. HVDC SYSTEM AND CONVERTER

The HVDC system is represented by the CIGRE first HVDC Benchmark model which is mainly used for the simulation study of the HVDC transmission systems [9]. The CIGRE HVDC system is mono-polar and each rectifier and inverter station is rated 500kV, 1000MW. The rectifier side is connected to a relatively strong AC system. The rectifier and the inverter are interconnected through a 300 km distributed parameter line and two 0.5 H smoothing inductor.

A. Converter Station

The basic model of an HVDC converter is the three-phase, full-wave bridge circuit. The DC transmission line is described by T network. Each converter has a 12-pulse bridge using two 6-pulse Thyristor bridges connected in series. The reactive power required by the converters is provided by a capacitive reactive compensation.

B. Rectifier and Inverter Control

Mainly, the CIGRE HVDC benchmark system consists of two control model. The rectifier control is provided with a Constant Current (CC) controller to maintain the DC link current constant and the inverter is equipped with a Constant Extinction Angle (CEA) controller and the CC controller. The DC link current at the rectifier end is compared with reference current which obtained from the inverter controller output to produce error signal [10]. By subtracting the measured current with reference current and input signal u_1, the error signal is obtained. The error signal is then passed through the PI controller to produce required firing angel α at rectifier valves. The current controller block diagram for rectifier is shown in Figure 1.

The rectifier, moreover, is provided with an α limit control. In the CC control mode, tap changer control of the converter transformer brings α within range of 10° to 20°. The rectifier fringe angle decreases until it reach the $\alpha_{\min}$ limit, if there is a reduction in voltage at the rectifier end. Under normal conditions, nominal angle in rectifier control (α) is regulated to a value of about 15°.

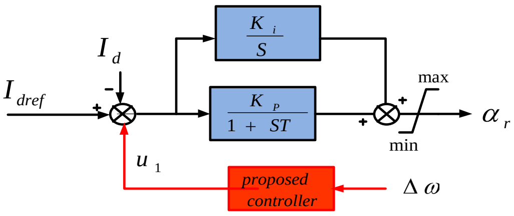

Figure 1. Rectifier current controller

III. THE OCCURRENCE OF SUB-SYNCHRONOUS TORSIONAL OSCILLATIONS (SSTO)

To clarify the SSTO, the shaft system of a turbine-generator unit which consist of several masses of different sizes, can be lumped together to form a multi-mass model. This set can be viewed as mass-spring-damper system according to Figure 2 [6].

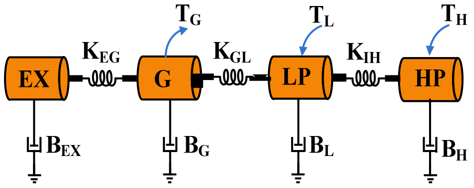

Figure 2. Lumped mass-spring system

The equation of motion for shaft sections which are connected to each other is described by:

$$T_m - T_e = J\frac{\partial P_e}{\partial t} + D\omega \tag{1}$$

$$\frac{\partial \delta}{\partial t} = \omega - \omega_o \tag{2}$$

where T_m is the mechanical torque applied to each mass and T_e is the electrical torque produced by the generator. ω is rated speed (rad/sec).

$$T_e = \frac{P_e}{\omega_g} \tag{3}$$

$$D_e = \frac{\partial T_e}{\omega_g} \tag{4}$$

From Equations (3) and (4):

$$D_e = \frac{\partial P_e}{\omega_g} - P_{eo} \tag{5}$$

and the power flow equation of the system is:

$$P_e = P_{dc} + P_{ac} \tag{6}$$

The adverse SSTO effects will be experienced when HVDC converter station is electrically connected close to a generator. The following reason will influence in this phenomenon. Primarily, the HVDC converter appears as a constant power load to the AC transmission system, at least within the bandwidth of the power or current control [6]. According to (5), constant power load provides a negative influence on the damping because of constant power. So, the first term in (5) is zero. Hence, this negative damping characteristic is directly related to HVDC power level.

The influence of the current or power control depends on the regulator bandwidth. These controls have a band width in range of 10 to 20 Hz and just the torsional modes that have frequencies below the upper range of the band width are effective for becoming unstable [16].

The other factor that influence in the interaction, is the rating of the dc system in relation to that of the generating unit. According to the simulation which is shown in the Figure 3, the SSTO will occur, if the rating of the DC system is above 0.6 pu.

Obviously, the turbine-generator units that are feeding an HVDC line radially are most prone to unfavorable torsional interaction. The unit interaction factor (UIF) is an approximate relationship between the magnitude of the interaction and ac system strength has been developed [11].

$$UIF = \frac{MVA_{dc}}{MVA_g}(1-\frac{SC_g}{SC_t})^2 \tag{7}$$

where

MVA_{dc} : rating of the HVDC

MVA_g : rating of the generator

SC_g : Short-Circuit Capability at HVDC commutating including the generator

SC_t : Short-Circuit Capability at HVDC commutating excluding the generator

A unit with an interaction factor that is less than about 0.1 will not has significant interaction between the torsional oscillation and the DC controls and can be neglected. According to the system data in the Appendix I, the interaction factor for the rating of the DC system at 0.8 pu equals to o.158 that is greater than 0.1. Hence, a strong interaction between the converter and the synchronous machine unit is expected in this case. But for the rating of the DC system at 0.4 pu, UIF is nearly 0.079 and this is in accordance to the accepted required UIF values ($UIF < 0.1$), which resulted in the stability of the torsional mode.

Figure 3 shows an extended simulation of the system for purpose of comparison with response obtained from UIF consequences. To modify the possibility of torsional instability, a parallel AC line with HVDC transmission system is suggested.

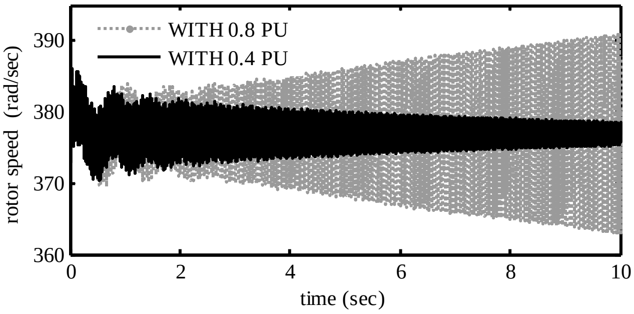

Figure 3. Simulated rotor speed response for rating of the dc system at 0.8 and 0.4 pu

IV. SUBSYNCHRONOUS RESONANCE IN POWER SYSTEM

One of the conventional series compensators in power systems are series capacitors that are employed for compensation of the inductive reactance of the transmission lines. This device has been widely used in AC transmission system to enhance the power transfer capability with reducing the line reactance. However, series compensation causes to dynamic instability and subsynchronous resonance (SSR) problems that occur mainly in series capacitor compensated transmission system. The series capacitors coupled with line reactance perhaps can activate oscillatory modes inherent in the mass-spring system of turbine generators, resulting in subsynchronous resonance. SSR is a potential phenomenon which may arise in a power system when the mechanical system (turbine-generator) exchanges energy with the electrical network [12]. The series-compensated line would include sub synchronous currents with electrical frequency.

$$f_e = f_o\sqrt{\frac{x_c}{x_{eq}}} \tag{8}$$

where, x_c is the series capacitor reactance, x_{eq} is the equal reactance of the transmission line, generator and transformer, also f_o stands the nominal frequency of power system. The generated sub-synchronous currents will result in rotor torque at the complementary frequency, i.e.

$$f_r = f_o - f_e \tag{9}$$

Under such conditions, torsional oscillations can be excited if difference between synchronous frequency and natural frequency (the line include series capacitor compensated) of the network is close to one of the torsional frequencies of the turbine-generator shaft system [7].

V. STATCOM CONTROLLER FOR SSR AND SSTO MITIGATION

This section addresses the STATCOM control circuit in order to mitigate SSR and SSO in an HVDC system in parallel with an AC line. The control algorithm in the base case is corresponding to the voltage regulation.

A. Base Case

The STATCOM is a power electronic based Synchronous Voltage Generator (SVG) that generates a three-phase voltage in synchronism with the transmission line voltage from a DC capacitor. Generally, it is connected to the transmission line by a coupling transformer. By controlling the output voltage magnitude of the STATCOM, the reactive power will be exchanged between STATCOM and the transmission system. The STATCOM is based on the principle that regulates the voltage at its terminal with managing the amount of reactive power injected to or absorbed from the power system. When the system voltage is going to decrease, it generates a reactive power (capacitive mode).

In a similar manner, if the system voltage is high, it will absorb reactive power (inductive mode). The voltage source converter (VSC) which is linked to secondary side of the coupling transformer contributes to perform the variations of the reactive power. The VSC uses forced commutated power electronic devices (GTOs, IGBTs or IGCTs) to create a voltage from a DC voltage source [13].

B. STATCOM Controller

In order to control the power electronic switches, Sinusoidal Pulse Width Modulation (SPWM) is utilized. This algorithm is implemented to synthesize a sinusoidal wave form proportional in magnitude to the modulation gain (k) and shifted by the phase angle α. The supreme merit of pulse width modulation is that, both parameters k and α can be independently controlled. As the phase angle of the voltage on converter side is changed with respect to the phase angle of AC system voltage, the STATCOM will attempt to generate or absorb active power form the AC system. The exchanged active power will charge or discharge the internal DC capacitors [14].

The primary duties of a STATCOM are to control the AC line voltage (v_s), and the DC capacitor voltage (v_d). The AC voltage control is achieved by filtering out the second harmonic and the low frequencies of the AC voltage and then a lead-lag and PI controller are applied to the voltage error in order to attain the modulation phase shift α. The DC capacitor voltage error is put through a PI controller to provide the modulation index gain k. Figure 4 shows the control block of the STATCOM [14].

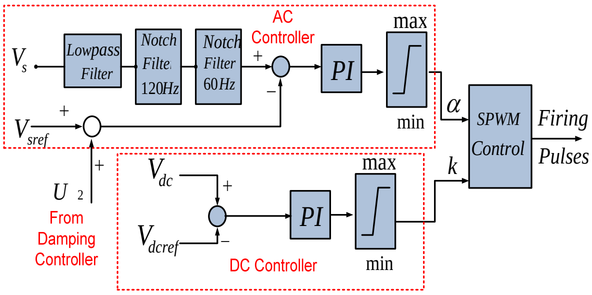

Figure 4. Block control of STATCOM

VI. POWER SYSTEM CONFIGURATION FOR SSR AND SSTO STUDY

The system investigated here, is the IEEE second benchmark model (SBM) in parallel with an HVDC model that is based on CIGRE HVDC benchmark system and is depicted in Figure 5 [15]. The mechanical part of the generating unit is a mass-spring system containing four masses: The High Pressure turbine (HP), the Low-Pressure turbine (LP), the Generator (GEN), and the Exciter (EX) are all coupled on the same shaft. The purpose of this research is to damp the SSR and SSTO with SSTODC of HVDC system and a new Auxiliary Damping Signal for STATCOM (ADSS) and a comparison between them.

The Fast Fourier Transform (FFT) of the generator rotor speed is performed among 2-10 second with time division of 2 second which is shown in Figure 6. The result of FFT analysis is used to access the system modes due to SSTO without series compensator in power systems with $P_{dc} = 0.8$ pu. An FFT analysis is also accomplished on generator rotor angular speed between 2 and 4 second in order to obtain the oscillatory modes of the system which is shown in Figure 7. It is observed that three critical modes are included: torsional modes 1.5, 24.5 and 32.15 that exist in the generator rotor speed and the torque signals of various turbine stages (The 49 HZ is not sufficient mode). It can be seen that 24.5 HZ is the most dominant mode. The frequency of 1.5 Hz is a low frequency oscillation mode.

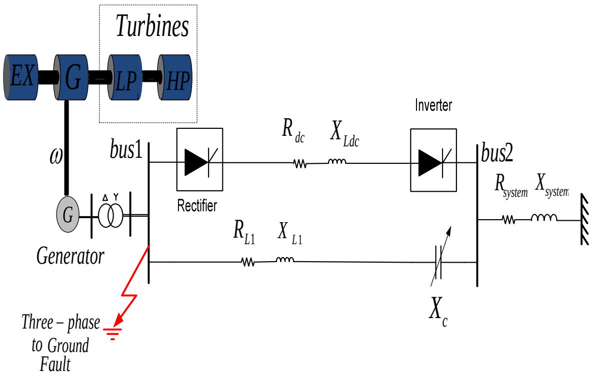

Figure 5. IEEE second benchmark model with an HVDC link included

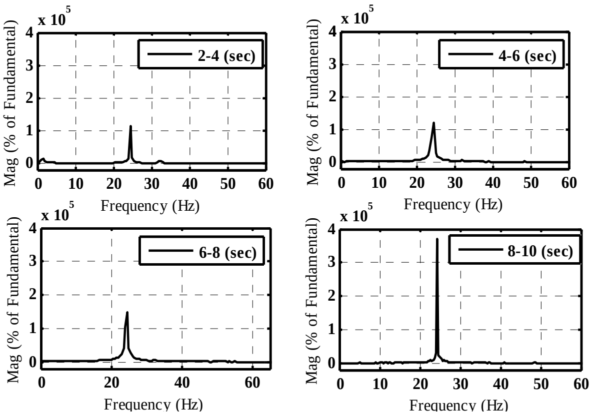

Figure 6. FFT analysis on generator rotor speed (without series compensator in $P_{dc} = 0.8$ pu)

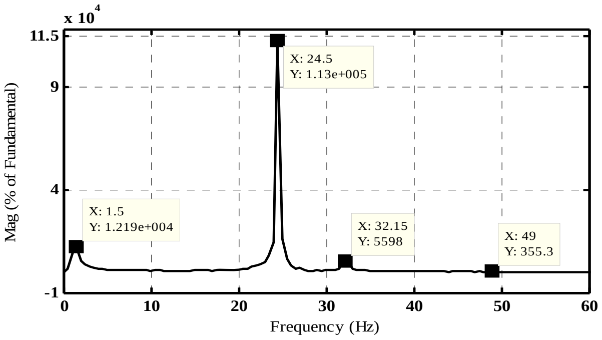

Figure 7. Torsional modes of generator rotor speed

VII. DESIGN CONCEPT OF SSODC AND ADSS

As described in section II-B, the direct current is the basic controlled quantity in an HVDC transmission which is controlled by the rectifier. The HVDC link may either be in parallel with AC system. With modulating the current required at the rectifier, damping of the AC system's electromechanical oscillations can be increased. The supplementary controller's main objective is to improve damping of oscillations which are caused by SSTO and SSR. The compensator generally consists of a washout and a series of lead and/or lag functions. The procedure for designing the supplementary control is shown in Figure 8 is a compensator with feedback signal $\Delta\omega$ (generator speed deviation).

Also two supplementary damping signals u_1 and u_2 can employed to generate. The suggested block diagram of the SSODC consists of the gain k and a stage washout filters is used to reduce the gain at low frequencies and a stage lead-lag block is used to compensate for the phase lag due to the current controller. The signal that obtained by comparing I_{dc} with I_{dcref} arrive to rectifier controller and is used to control the direct line current. It should be noted that, the output of ADSS is employed to modulate the reference value of AC voltage in STATCOM in order to produce the proper damping. The controller parameters are reported in the Appendix 1.

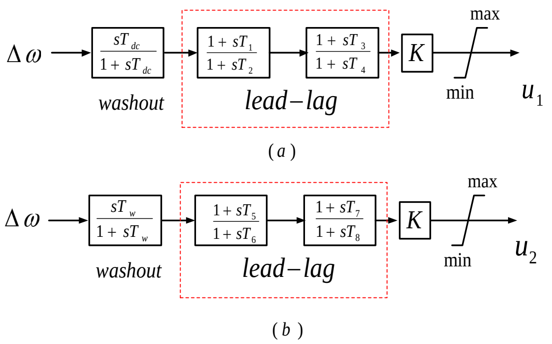

Figure 8. Block diagram of the (a) SSODC and (b) ADSS

VIII. SIMULATION RESULTS

This section is dedicated to scrutinize the SSTO and SSR influence in power system. For more details about the system data see Appendix 2. A three phase-to-ground fault located near the bus 1 which occurs at t=0.022 seconds and lasts for 16.9 milliseconds. Firstly, the results without any controllers are clarified that are shown in Figure 9 (a-d). These figures show that the system is completely unstable duo to this phenomenon. So, there should be a controller in order to control these amplifications and damp the SSR. The suggested controller has been applied at two different cases to evaluate the controller performance in SSR and SSTO mitigation.

In each case, simulations are repeated in three stages to show the superior performance of the proposed damping control system. In first stage, SSOD controller is applied to the rectifier current regulator. In the second an ADSS is granted to the STSTCOM angle regulator, and on the sequel, both controllers will improve the unstable operation of the system. Simulations results are obtained for each case separately and are carried out using Matlab/Simulink.

A. Scrutiny Damping of SSTO with SSODC and ADSS

Figures 10 and 11 show the responses of GEN-LP and LP-HP shaft torque and rotor speed with SSODC and ADSS. The figures show that the torsional oscillations are well damped with both controllers. In this section the rating of the HVDC system is 0.8 pu and AC system is without series compensation in order to clarify the effect of SSTO.

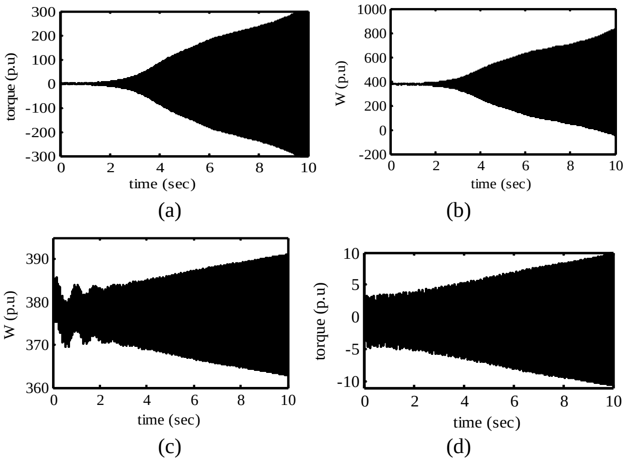

Figure 9. (a), (b) simulated rotor speed and generator shaft torques sequence due to SSR and (c), (d) due to SSTO

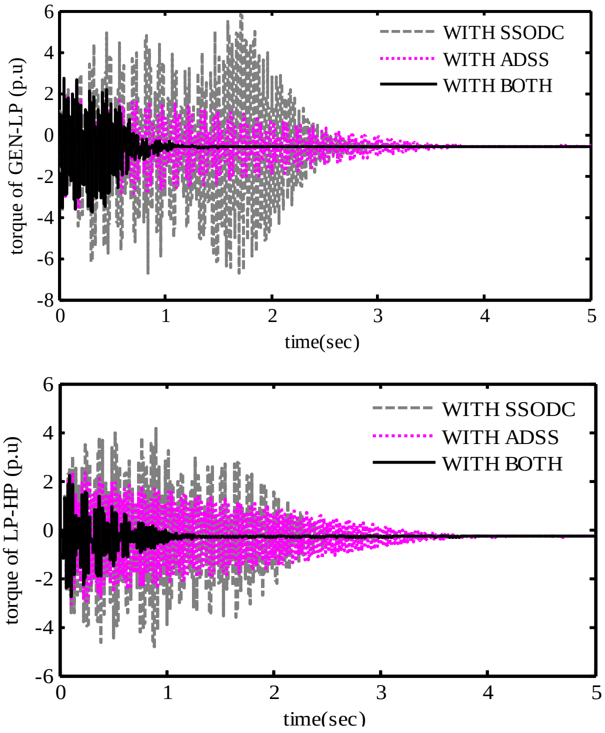

Figure 10. Torsional oscillation response with ADSS and SSODC

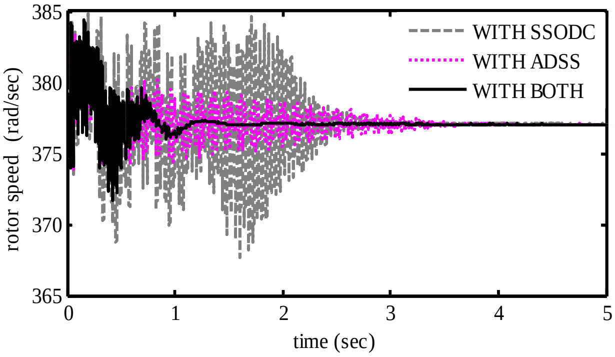

Figure 11. Generator rotor speed response with ADSS and SSODC

B. Scrutiny Damping of SSR with SSODC and ADSS

Now, consider a condition in which the series capacitor is linked to the system in order to verify the capability of controllers in SSR suppression. Figures 12 and 13 illustrate the responses for generator rotor speed and also the torques between different sections of the turbines in 3 cases. These figures clearly demonstrate the impressiveness of the SSODC and ADSS in providing positive damping for the SSR modes under disturbance conditions.

Figure 14 exhibits the generator rotor speed when both of the controllers are applied to the system. It has been showed that beside of sub-synchronous mode oscillation at 24.5 Hz, a low frequency oscillation at 1.5 Hz is faced to rotor speed which is specified separately in Figure 14. For this section, the AC line is compensated with Series capacitors and rating of the DC system is 0.4 pu in order to preserve from SSTO.

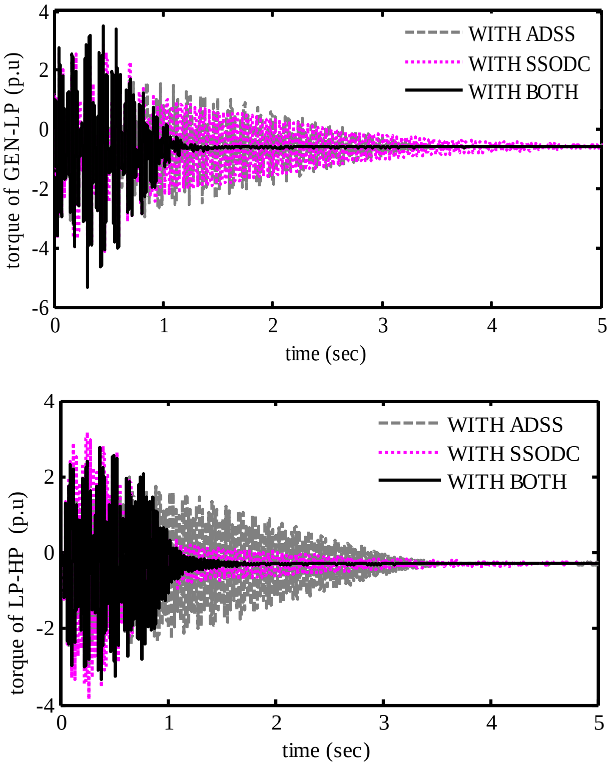

Figure 12. Sub-synchronous resonance response with SSODC and ADSS

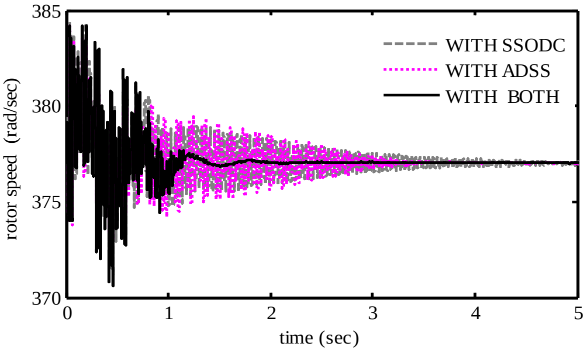

Figure 13 . Generator rotor speed response with SSODC and ADSS

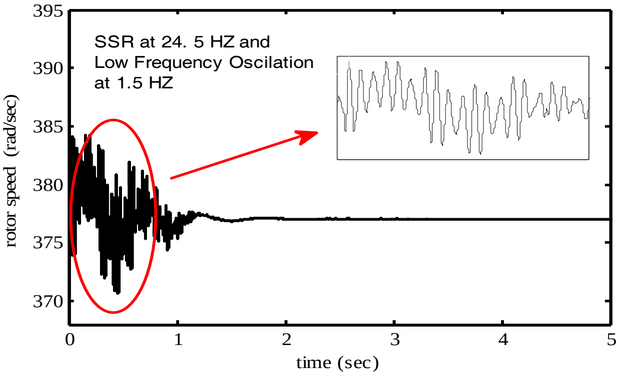

Figure 14. Generator rotor speed in presence of both controller.

IX. CONCLUSIONS

In this paper, analysis and damping the phenomena of SSR and SSTO has been studied. It has been shown that, the SSTO will increase with increasing power ratings of HVDC system. Furthermore, for mitigating of SSTO and SSR, a supplementary sub-synchronous oscillation damping controller (SSODC) is equipped at the rectifier end of an HVDC link connected in parallel with an AC line. Also, the damping of suggested SSTO and SSR is yielded by STATCOM which is connected at the middle of the AC line. When the supplementary controllers are employed in the system, both controllers are effective in damping all the shaft torsional torques separately. Simulation results and FFT analysis on rotor speed demonstrate that, implementation of two auxiliary controllers in each line (DC system and AC line) together can yield the goal of alleviation in superior manner. As illustrated, when two damping controllers are considered to perform concurrently, beside of their common function such as Voltage regulation, active and reactive power control and also reactive power compensate, the best achievable damping of SSR or SSTO has been obtained.

APPENDICES

Appendix 1. The SSODC and ADSS Controller Parameters

- The SSODC Controller Parameters

$k = 35$, $T_{dc} = 2$, $T_1 = 0.05$, $T_2 = 0.02$, $T_3 = T_4 = 0$

- The ADSS Controller Parameters

$k = 1000$, $T_{\omega} = 0.94$, $T_5 = 0.26$, $T_6 = 0.3$, $T_7 = 0.106$, $T_8 = 0.05$

Appendix 2. System, HVDC, Network Data

- Detailed System Data - HVDC System [9]
Rating 1000MW, mono-polar, DC voltage 500 kV, DC current 2000 Amps, length of the DC line 300 km, Converter transformer leakage reactance 0.18 pu
- Synchronous generator [15]
Nominal rating: $S = 600$ MVA
- Network
Nominal voltage: 500 kV
Short-circuit power: SC = 3333 MVA

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BIOGRAPHIES

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Morteza Farsadi was born in Khoy, Iran in 1957. He received his Ph.D. in Electrical Engineering (High Voltage) from Department of Electrical and Electronics Engineering, Middle East Technical University, Ankara, Turkey and Istanbul Technical University, Istanbul, Turkey in 1989. He is now an Assistant Professor in the Department of Electrical Engineering, Urmia University, Urmia, Iran. His main research interests are in high voltage engineering, industrial power system studies and FACTS.