HVDC-Generator-Turbine Torsional Interaction Studies Using A Linearized Model With Dynamic Network Representation

Chandana Karawita and U.D. Annakkage

***Abstract*—This paper demonstrate the capabilities of the small signal stability assessment to identify the HVDC-generator-turbine torsional interactions. Modal analysis of the linearized state space model of the power system is used in the small signal stability. It is required to obtain the linearized models of power systems including transmission network dynamics and generator stator winding dynamics in order to obtain meaningful results in the subsynchronous frequency range. The modal analysis techniques are further utilized to design subsynchrnous damping controllers at the HVDC links. The results are validated using electromagnetic transient simulations.**

***Keywords*: HVDC, Torsional oscillations, Small Signal Stability.**

I. INTRODUCTION

HVDC controller interaction with generator-turbine systems is a torsional destabilizing phenomena which may occur when HVDC and generator-turbine units are tightly coupled. These torsional interactions, which lie in the subsynchronous frequency range (0 to fundamental frequency), occur between the rectifier current/power controller and the multi-mass rotor-turbine systems of the generators [1]. In some practical cases, torsional instabilities caused by HVDC-generator-turbine interactions have been reported [2] [3]. Therefore, the possibilities of subsynchronous instabilities should be thoroughly analyzed while designing and tuning HVDC controllers.

Although, the HVDC controllers may cause torsional instabilities in generator-turbine units, they can also be utilized to improve the damping of the torsional modes. A subsynchronous damping controller (SSDC) can be included in rectifier current/power controller as an auxiliary controller [4]–[7]. SSDC consists of gain blocks, washout filters and lead-lag blocks to appropriately damp out one or more troublesome torsional modes.

Small signal stability assessment technique can be employed to analyze subsynchronous oscillations in detail. The dynamic behavior of a power system is obtained around a steady state operating point using eigenvalues and eigenvectors of the linearized model [8]. In addition to that, the small signal stability assessment technique can also be employed to design SSDCs for HVDC-generator-turbine systems [7]. However it is required to use appropriately linearized models in order to obtain accurate results throughout subsynchronous frequency range.

When linearized models are used to study the damping of low frequency electromechanical oscillations in power systems, the transmission network is modeled using the bus admittance matrix and the generator stator winding dynamics are ignored. However, the frequencies associated with torsional oscillations are much higher than those of electromechanical oscillations. Therefore, simplified network models and generator models are not adequate.

This paper demonstrates that a linearized model with dynamic representation of the transmission network and stator dynamics modeled for the generators is adequate for studying subsynchronous oscillations. A simple test system, in which a generator and an HVDC system are tightly coupled is used in the analysis. For validations, small signal responses obtained using linearized models are compared with more accurate Electromagnetic Transient (EMT) Simulation results. Possible torsional instabilities which may occur due to HVDC controller tuning are identified using small signal stability models and validated using EMT simulations. SSDC design procedure for the test system is described using small signal stability assessment.

The paper is organized as follows. Section II describes the test system and the linearized model of it used in the analysis. The small signal stability of the test system is assessed in section III. The conclusions are made in section IV.

II. TEST SYSTEM

The CIGRE bench mark HVDC test system [13] with some modifications is used to analyze subsynchronous oscillations. A synchronous generator is connected at rectifier side AC bus to supply half of the P-Q requirement of rectifier. The generator-turbine parameters are as given in [10]. The exciter mass is not included in the analysis. The effective short circuit ratios (ESCR) without the synchronous generator were kept around 4.4 at the rectifier and the inverter ends. The test system is shown in Fig. 1.

A. Linearized Model

In order to analyze the subsynchronous oscillations accurately, following models are included in the linearized model.

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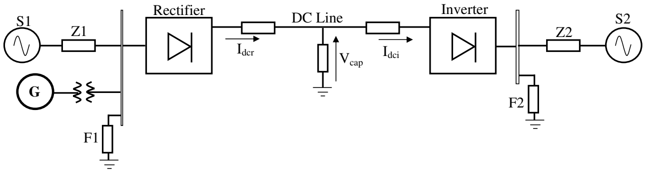

Fig. 1. Test System

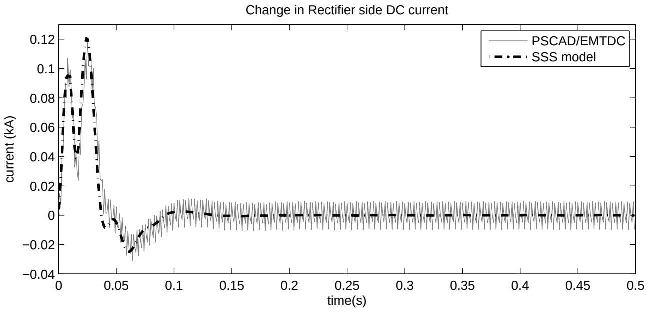

Fig. 2. Changes in rectifier side DC currents for a 10%, 10ms pulse on the rectifier current controller input

- Synchronous generator model including stator dynamics. For round rotor type, an 8^{th} order model is used. The linearized model can be found in [9]. An exciter model (AC4A) is also included with the generator model.
- A four-mass turbine model (HP, IP, LPA and LPB) as described in [10].
- HVDC system with linearized converter models, DC transmission system, rectifier current controller and inverter extinction angle controller as in [11].
- A dynamic AC network model as described in [11], [12].

The accuracy of the linearized models are evaluated using time domain simulations. Small perturbation simulations obtained using the linearized model are compared with EMT simulation results obtained using PSCAD/EMTDC.

A pulse of magnitude of +10% and duration of 10ms was applied to the rectifier current controller input. The change in rectifier side DC current is shown in Fig. 2. All the high frequency oscillations except higher order system harmonics match with the PSCAD/EMTDC results. Note that, the higher order harmonics of the HVDC system (eg: 12th harmonic in DC side) are not modeled in the small signal model and therefore those available in PSCAD/EMTDC simulations are ignored when comparing with the small signal model. Fig. 3 shows changes in the generator speed. Small signal model results show a very close match with the PSCAD/EMTDC results for the subsynchronous frequencies embedded in the generator speed. These comparisons verify that the linearized model with the level of details considered above accurately represent the subsynchronous oscillations in the system. Therefore, the linear state space model can be used to analyze these oscillations using small signal stability assessment.

III. SMALL SIGNAL STABILITY ASSESSMENT

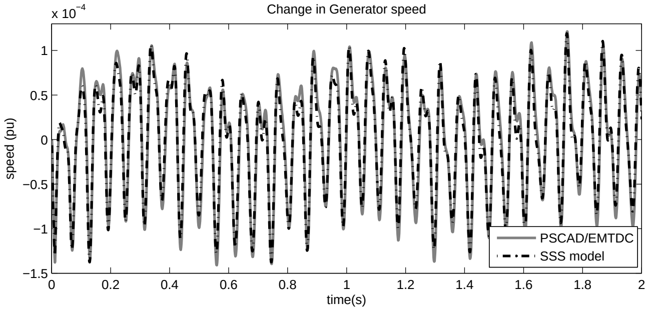

Fig. 3. Changes in generator rotor speed (in pu) for a 10%, 10ms pulse on the rectifier current controller

TABLE I
SOME IMPORTANT MODES OF THE TEST SYSTEM

Mode	Freq. (Hz)	D (%)	Major Participant
1	16.33	7.81e-2	Gen-Turbine (SSO)
2	25.60	9.75e-3	Gen-Turbine (SSO)
3	32.53	1.02e-2	Gen-Turbine (SSO)
4	47.46	2.92e-6	Gen-Turbine (SSO)
5	10.33	51.9	Rectifier Current Controller
6	42.32	22.7	DC line
7	1.36	3.2	Generator (Electromechanical)

The small signal model of the test system consists of 60 state variables: generator-turbine system (19), HVDC system (9) and AC network including filters (32). Some important modes obtained under nominal operating conditions are shown in Table I. The generator-turbine system shows 4 torsional oscillation modes (Modes 1 to 4). The frequencies of oscillations are 16.33, 25.6, 32.53 and 47.46Hz respectively. Although the mechanical damping of multi-mass system is ignored, these modes show very low damping caused by the electrical torque. The state variables of the rotor mass system participate in these modes.

The rectifier current controller state variable and the DC line state variables participate the most in Modes 5 and 6. There are some minor participations of the generator speed in these modes. These modes are also in subsynchronous frequency range (10.33 and 42.32Hz). However, these modes are well damped.

The electromechanical mode of the system is given by Mode 7. The frequency of oscillation is 1.36Hz and the mode has 3.2% damping.

A. HVDC-Generator-Turbine Torsional Interactions

Under given conditions, the test system does not show any interactions between the HVDC system and generator-turbine system. However, there might be some interactions if the operating conditions are changed or the controller parameters are changed. In order to demonstrate this, the analysis was carried out by changing the rectifier current controller proportional and integral gains. It was observed that, if there is a slightly damped HVDC controller mode, in which the frequency is very close to a torsional mode of the generator-turbine system, the two systems might interact strongly even causing instabilities. When the rectifier current controller proportional gain is 0.11 and the integral time constant is 0.0045s, the controller mode (Mode 5) gets close

TABLE II
PARTICIPATING MODES IN TORSIONAL INTERACTIONS WHEN CONTROLLER GAINS ARE ADJUSTED

Mode	Freq. (Hz)	D (%)	Major Participants
A	16.24	-0.03	HVDC-Generator-Turbine
B	16.36	1.05	HVDC-Generator-Turbine

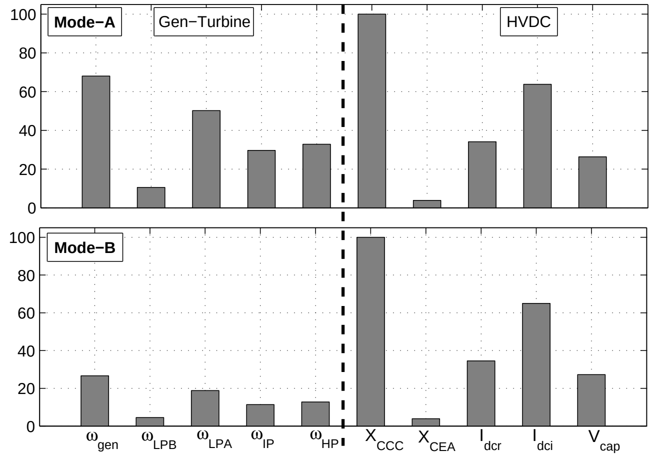

Fig. 4. Participation factors (%) of multi-mass speed terms and HVDC state variables in Modes A and B

to Mode 1 (torsional mode) in frequency and the resultant torsional mode becomes unstable. The resultant modes close to Mode 1 are shown in Table II. The participation factors (%) of multi-mass speed terms (ω_{gen}, ω_{LPB}, ω_{LPA}, ω_{IP}, ω_{HP}) and HVDC state variables [rectifier current controller state variable (X_{CCC}), inverter extinction angle controller state variable (X_{CEA}), rectifier side DC current (I_{dcr}), inverter side DC current (I_{dci}) and midpoint capacitor voltage (V_{cap})] in these modes are illustrated in Fig. 4.

Mode-A is negatively damped and the frequency is at 16.24 Hz. The state variables of the generator-turbine system and the HVDC system strongly interact with each other in this mode (Fig. 4). The HVDC system state variables: X_{CCC}(100%), I_{dci}(60%) and I_{dcr}(30%) and the generator-turbine system state variables: ω_{gen}(70%), ω_{LPA}(50%), ω_{IP}(30%) and ω_{HP}(30%) are the major participants.

The HVDC state variables participate the most in slightly damped Mode-B (Fig. 4). The frequency is at 16.36 Hz and the damping is 1.05 %. HVDC system state variables: X_{CCC}(100%), I_{dci}(60%) and I_{dcr}(30%) are the major participants. There are some participations of the multi-mass speed terms as well [ω_{gen}(20%), ω_{LPA}(20%)].

The comparisons of the change in rectifier side DC current and the change in generator speed for the perturbation mentioned earlier are shown in Fig. 5 and 6 respectively. Mode-A can be observed in the unstable oscillations of the generator speed (Fig. 6) and Mode-B can be observed in the rectifier side DC current (Fig. 5). The close match with the PSCAD results further demonstrate the accuracy of the small signal model in identifying the torsional interactions.

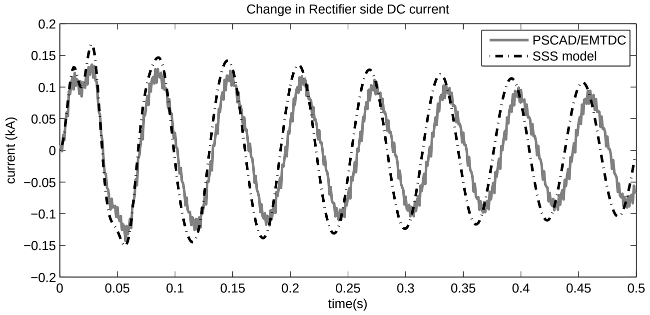

Fig. 5. Changes in rectifier side DC currents for a 10%, 10ms pulse on the rectifier current controller input (when current controller gains are adjusted)

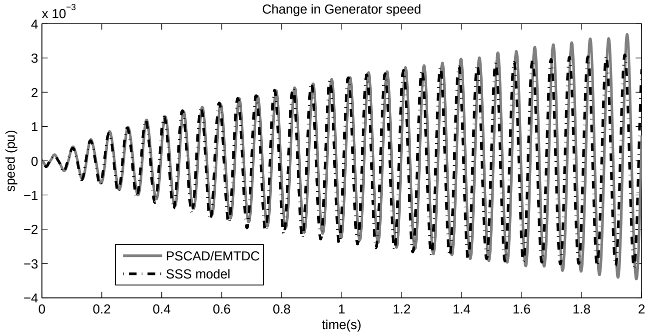

Fig. 6. Changes in generator rotor speed (in pu) for a 10%, 10ms pulse on the rectifier current controller (when current controller gains are adjusted)

If the AC network dynamics are ignored (admittance matrix model), the small signal model shows inaccurate results. In this model, Mode-A is at 16.3Hz with +0.07% damping. According to this, the torsional mode is stable. Furthermore, Mode-B is at 18.4Hz and it has +4.7% damping. These results are very different from the results presented in the above analysis. Therefore, the admittance matrix representation is not adequate to analyze torsional interactions accurately.

It was found using the small signal model that there is a similar torsional instability in the generator-turbine system when the rectifier current controller proportional gain is 2.8571 and the integral time constant is 0.0012s. This produces a controller mode close to Mode 2 ($\approx 25Hz$) and causes instability in the torsional mode.

In conclusion, the HVDC-generator-turbine interactions may happen if there is a slightly damped HVDC controller mode in which the frequency is close to a torsional frequency in the system. These conditions may even lead to torsional instabilities. The small signal stability assessment can be employed to identify the conditions for these torsional instabilities.

B. Design of SSDC Using Small Signal Stability Assessment

The same procedure, which is followed to tune power system stabilizers (PSS) [14] can be employed to design SSDCs attached to the HVDC system. The torsional modes in the generator-turbine system can be controlled through the rectifier current controller input.

The controllability of the modes can be analyzed using the mode controllability indices as described in Chapter 12 of [8]. For the above mentioned test system under nominal conditions,

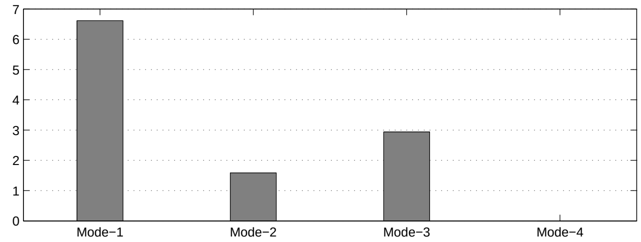

Fig. 7. Controllability of torsional modes through rectifier current controller input

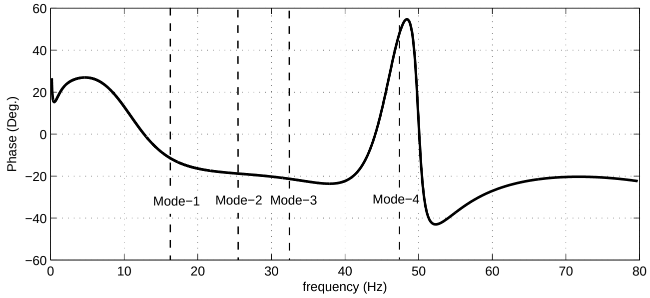

Fig. 8. Phase plot of frequency response between generator electrical torque and rectifier current controller input

the magnitudes of the controllability indices obtained between four torsional modes (Table I) and the current controller input are illustrated in Fig. 7. Mode-1 (16.33Hz) is the most controllable mode among the torsional modes. Modes 2 and 3 are also controllable using the current controller input. However, Mode-4 (47.46Hz) can not be controlled using the current controller input.

The first three torsional modes can be observed in the generator speed and therefore, the speed can be used as an input to the SSDC.

In order to provide positive damping at required frequency range, the SSDC should have an appropriate phase characteristic to compensate for the phase lag/lead between the current controller input and the electrical torque of the generator. The frequency response for the transfer function between the current controller input and the electrical torque is obtained while keeping the generator rotor angle constant (this can be done by increasing the inertia to a very large value) [14]. The phase characteristics of the test system obtained as described, is shown in Fig. 8. The transfer function shows a phase lag of 10^o to 20^o in the range of frequencies corresponding to Modes 1, 2 and 3. At the frequency of Mode-4, the system shows a phase lead of around 50^o. We are not concerned about this mode because it is neither observable in generator speed nor controllable through the current controller input.

One lead-lag block with a phase lead of 10^o at 25 Hz ($T_1 = 0.0076s,\ T_2 = 0.0053s$) is used to compensate the phase lag in the corresponding frequency range. A washout filter ($T_w = 20s$) is also included to block the steady (DC) changes in the speed [14].

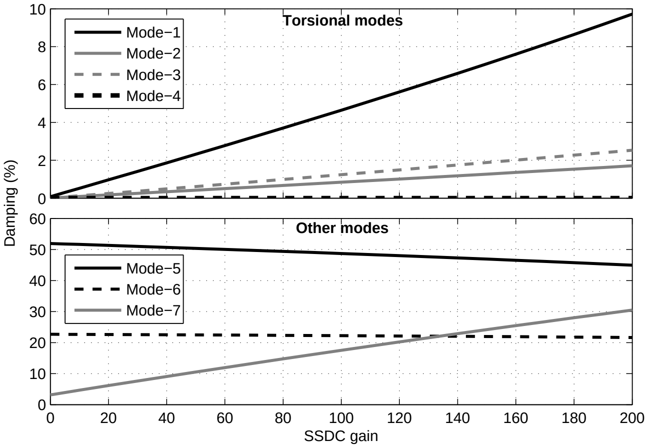

Fig. 9. Changes in mode dampings with SSDC gain

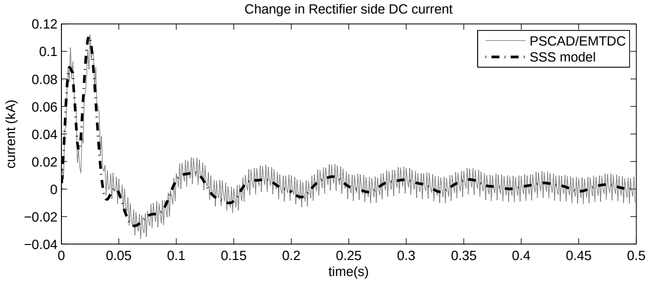

Fig. 10. Changes in rectifier side DC currents for a 10%, 10ms pulse on the rectifier current controller input (when SSDC is connected at rectifier)

The SSDC gain is adjusted to improve the damping of torsional modes, while keeping the damping of other modes at appropriate levels. Fig. 9 shows the damping versus SSDC gain characteristics obtained for the torsional modes and the other modes in the range of 0 to 200 of SSDC gain. As the gain increases the damping of Mode-1 increases significantly. Around 5% damping can be obtained when the gain is 100. The damping of Modes 2 and 3 also increases as the gain increases. There is no any improvement in Mode-4, since it is uncontrollable through the SSDC. The decrements in damping of HVDC system modes (Mode 5 and 6) are comparatively small and the damping factors are at acceptable levels. The SSDC helps to improve the damping of electromechanical mode (Mode-7) as well. Around 18% damping can be obtained when the gain is 100.

Based on the above observations, the SSDC gain is set at 100, in order to obtain 5% damping in the first torsional mode (Mode-1). Furthermore, this does not cause any adverse effect on the other modes. Small perturbation simulations are used to demonstrate the performance of the developed SSDC in damping the oscillations in the generator-turbine unit. For the pre-described perturbation, the changes in rectifier side DC current and the generator speed are compared in Fig. 10 and Fig. 11 respectively. Some oscillations in the rectifier side DC current can be observed due to the introduction of SSDC. However, the oscillations die down fast. A very good improvement in the generator speed compared to the case without SSDC (Fig. 3) can be observed . The torsional oscillations decay within 2s when the SSDC is introduced.

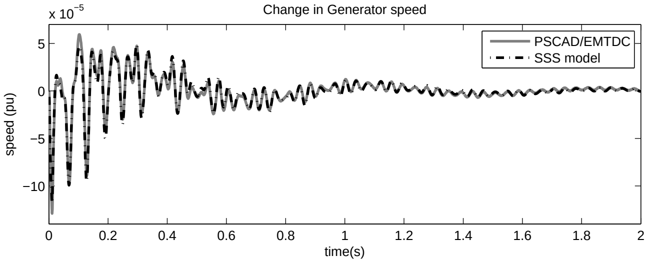

Fig. 11. Changes in generator rotor speed (in pu) for a 10%, 10ms pulse on the rectifier current controller (when SSDC is connected at rectifier)

Furthermore, the comparisons given in Fig. 10 and Fig. 11 show a very good match of the results of the small signal model with the results of PSCAD/EMTDC. This demonstrates the adequacy of the small signal stability model for analyzing subsynchronous oscillations and for designing controllers to mitigate them.

The idea of this example was to demonstrate the basic concepts of designing SSDCs using small signal stability assessment. However, the performance of the SSDC has to be tested under different operating conditions such as different DC power output levels and under different transient conditions. The limits to the controller has to be enforced accordingly.

IV. CONCLUSIONS

A linearized model of a power system with dynamic phasor representation of the transmission network and the stator winding dynamics modeled for the generators is adequate to analyze HVDC-generator-turbine torsional interactions. The HVDC-generator-turbine torsional interactions may occur if there is a slightly damped HVDC controller mode, in which the frequency is very close to a torsional mode of the generator-turbine system. These interactions may even lead to torsional instabilities. This has been demonstrated using electromagnetic transient simulations. A damping controller has been introduced to the HVDC system to damp out the torsional oscillations. The design procedure has been discussed using small signal stability assessment.

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