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Analysis of Sub-Synchronous Resonance with VSC-Based HVDC System

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ABSTRACT: The main objective of this paper is to investigate and present the detailed analysis of Sub-Synchronous Resonance (SSR), arising from a VSC-based HVDC system connected close to generating units. The analysis considers different operating modes of the converters. Based on a case study, it is shown that the dc voltage control mode of VSC operation (rectifier/inverter) close to the generator units can contribute positive damping in the torsional-mode frequency range of interest. The investigations of SSR with VSC-based HVDC are carried out based on linear analysis and nonlinear transient simulation. While the damping torque, Eigen value analysis, and controller design are based on the D-Q model, the transient simulation considers the D-Q model and the three-phase detailed model of VSC using switching functions. The amplitude and phase angle of the converter ac output voltage can be controlled simultaneously to achieve rapid and independent control of active and reactive power in all four quadrants. For active power balance, one of the converters operates on dc voltage control and the other converter is on active power control. When dc line power is zero, the two converters can function as independent STATCOMs. At any converter, the two quantities to be controlled are 1) the ac bus voltage/reactive current and 2) the power/dc voltage. All controllers are of the PI type except the power controller which uses the PID type. The influence of the operating modes of the converters and effects of some important parameters, such as effective short circuit ratio and generator rating are investigated simulation are carried out using Matlab/Simulink.

KEYWORDS: Damping , Voltage Source Converter , Active Power , Reactive Power

I. INTRODUCTION

The VSC-based HVDC converter control can destabilize torsional modes of nearby turbo generator and have several advantages compared to conventional HVDC, such as independent control of active and reactive power, dynamic voltage support at the converter bus, possibility to feed to weak ac systems or even passive loads, reversal of power without changing the polarity of dc voltage , and no requirement of fast communication between the two converter stations. The control of active and reactive power is bidirectional land continuous across the operating range. For active power balance, one of the converters operates on dc voltage control and the other converter is on active power control. The amplitude and phase angle of the converter ac output voltage can be controlled simultaneously to achieve rapid and independent control of active and reactive power in all four quadrants. When dc line power is zero, the two converters can function as independent STATCOMs. The modelling and control design of VSCs, which use a12-pulse three-level converter topology, are given in and the modelling of VSC is based on 1) - variables (neglecting harmonics in the output voltages of the converters) and 2) phase variables and the modelling of switching action in the VSC which also generates harmonics. The Eigen value analysis and the controller design are based on the D-Q model while the transient simulation considers both models of the VSC. Each VSC has two decoupled controllers for regulating active and reactive current outputs of the individual VSC. The reference to the active current controller is set by the output of the dc voltage controller or power controller. An additional controller at a VSC is required if the ac bus voltage is to also be regulated which sets the reactive current reference. Thus, there are a large number of controller parameters which are optimized based on a systematic approach. Sub-synchronous resonance is a condition that can exist on a power system where in the network has natural frequencies that fall below the nominal 60 hertz of the network applied voltages. These frequencies appear to the generator rotor as modulations of the base frequency, giving both sub-synchronous and super synchronous rotor frequencies. with possible torsional fatigue damage to the turbine-generator shaft.

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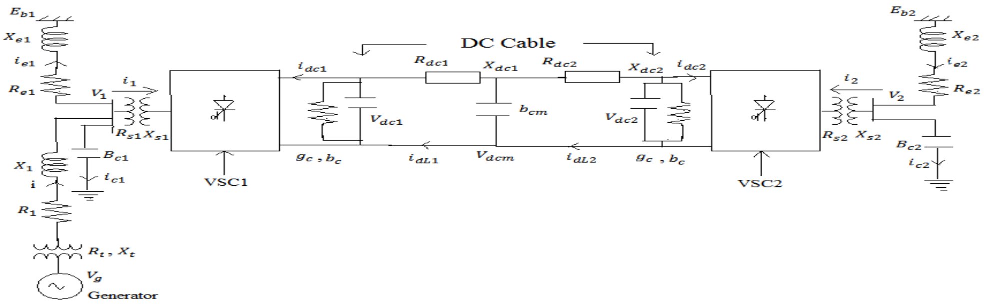
II. MODELLING OF VSC-BASED HVDC

The two-terminal VSC-based HVDC transmission system mainly consists of two converter stations connected by a dc cable. The study system consists of a generator and ac transmission system on either side of VSC HVDC cable transmission system.



System block diagram of the VSC-based HVDC transmission system.

The above figure shows the block diagram of the VSC based HVDC transmission system. The amplitude and phase angle of the converter ac output voltage can be controlled simultaneously to achieve rapid, independent control of active and reactive power in all four quadrants. The detailed three-phase model of converters is developed by modelling the converter operation by switching functions

III. MATHEMATICAL MODEL IN D-Q FRAME OF REFERENCE

When switching functions are approximated by their fundamental frequency components neglecting harmonics, the VSC based HVDC can be modelled by transforming the three-phase voltages and currents in to D-Q variables using Park's transformation with respect to a synchronously rotating reference frame. The magnitude control of the j^{th} converter output voltage V_j^i is achieved by modulating the conduction period affected by the dead angle β_j of the individual converters. One of the converters controls dc voltage while the other converter controls dc-link power. The output voltage of the j^{th} converter can be represented in the D-Q frame of reference as

$$V_j^i = \sqrt{(V_{Dj}^i)^2 + (V_{Qj}^i)^2}$$

$$V_{Dj}^i = k_{mj} V_{dcj} \sin(\theta_j + \alpha_j)$$

$$V_{Qj}^i = k_{mj} V_{dcj} \cos(\theta_j + \alpha_j)$$

Where

$$k_{mj} = k' \cos(\beta_j)$$

$$k' = k\rho_j V_{dcb} / V_{acb}$$

$$k = 2\sqrt{6}/\pi$$

For a 12-pulse converter, ρ_j is the transformation ratio of the interfacing transformer T_j, V_{dcb} and V_{acb} are the base voltages of the dc and ac sides, respectively. α_j is the angle by which the fundamental component of the j^{th} converter output voltage leads the j^{th} ac bus voltage V_j. With the two-converter VSC-based HVDC system $j = 1,2$.

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$$\frac{dI_{Dj}}{dt} = -\frac{R_{sj}\omega_B}{X_{sj}} I_{Dj} - \omega_0 I_{Qj} + \frac{\omega_B}{X_{sj}}[V_{Dj} - V_{Dj}^i]$$

$$\frac{dI_{Qj}}{dt} = \omega_0 I_{Dj} - \frac{R_{sj}\omega_B}{X_{sj}} I_{Qj} + \frac{\omega_B}{X_{sj}}[V_{Qj} - V_{Qj}^i]$$

The dc-side capacitors of the VSCs are described by the dynamical equations as,

$$\frac{dV_{dc1}}{dt} = -\frac{g_c\omega_b}{b_c}V_{dc1} - I_{dc1}\frac{\omega_b}{b_c} - I_{dL1}\frac{\omega_b}{b_c}$$

$$\frac{dV_{dc2}}{dt} = -\frac{g_c\omega_b}{b_c}V_{dc2} - I_{dc2}\frac{\omega_b}{b_c} + I_{dL2}\frac{\omega_b}{b_c}$$

Where $I_{dcj} = -[k_{mj}\sin(\theta_j + \alpha_j)I_{Dj} + k_{mj}\cos(\theta_j + \alpha_j)I_{Qj}]$

I_{Dj} and I_{Qj} and D-Q components of the jth converter current I_j.

I_{dL1} and I_{dL2} are the dc cable currents in the left- and right hand side sections of the cable and are described as

$$\frac{dI_{dL1}}{dt} = \frac{\omega_b}{X_{dc1}}[V_{dc1} - V_{dcm} - R_{dc1}I_{dL1}]$$

$$\frac{dI_{dL2}}{dt} = \frac{\omega_b}{X_{dc2}}[V_{dcm} - V_{dc2} - R_{dc2}I_{dL2}]$$

$$\frac{dV_{dcm}}{dt} = I_{dL1}\frac{\omega_b}{b_{cm}} - I_{dL2}\frac{\omega_b}{b_{cm}}$$

The real and reactive current controller forms an inner-loop control for all of the converters. The reactive current reference (I_{Rj}^*) of the jth converter can be kept constant or regulated to maintain the respective bus voltage magnitude at the specified value. It should be noted that the slope of the steady state ac voltage control characteristic is denoted by K_s. The active current reference (I_{Pj}^*) can be either obtained from the dc voltage controller or power controller as one of the converters controls the dc voltage and the other controls the dc-link power. Hence, at any converter, the two quantities to be controlled are 1) the ac bus voltage/reactive current and 2) the power/dc voltage. All controllers are of the PI type except the power controller which uses the PID type, the active and reactive currents for the jth converter are defined as

$$I_{Pj} = I_{Dj}\sin(\theta_j) + I_{Qj}\cos(\theta_j) \qquad \alpha_j = \tan^{-1}\left[\frac{V_{Rj}^*}{V_{Pj}^*}\right]$$

$$I_{Rj} = -I_{Dj}\cos(\theta_j) + I_{Qj}\sin(\theta_j) \qquad \beta_j = \cos^{-1}\left[\frac{\sqrt{(V_{Pj}^*)^2 + (V_{Rj}^*)^2}}{k'V_{dcj}}\right]$$

$$V_{Pj} = V_{Dj}^i\sin(\theta_j) + V_{Qj}^i\cos(\theta_j)$$

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$$V_{Rj} = V_{Dj}^{i}\cos(\theta_j) - V_{Qj}^{i}\sin(\theta_j)$$

Operating combinations of VSC-based HVDC

Case	VSC1(Rectifier)		VSC2(Inverter)	
	Controller-1	**Controller-2**	**Controller-1**	**Controller-2**
1	Power	Reactive current	DC Voltage	Reactive Current
2	Power	AC bus voltage	DC Voltage	AC bus Voltage
3	DC Voltage	Reactive current	Power	Reactive current
4	DC Voltage	AC bus voltage	Power	AC bus Voltage
	VSC1(Inverter)		**VSC2(Rectifier)**	
5	Power	Reactive current	DC Voltage	Reactive Current
6	Power	AC bus voltage	DC Voltage	AC bus Voltage
7	DC Voltage	Reactive current	Power	Reactive current
8	DC Voltage	AC bus voltage	Power	AC bus Voltage

The above Table show the operating combinations of VSC-based HVDC the various operating combinations of the VSC-based HVDC are summarized.. Each operating mode requires proper tuning of the controller gains in order to achieve satisfactory system performance. The controller parameters are selected based on a systematic approach

IV.SIMULATION RESULTS AND ANALYSIS

A CASE STUDY:

The VSC based HVDC transmission system diagram is shown in above which consists of a turbine generator on one side and an ac transmission system on either side of the VSC HVDC cable transmission system. The data for the turbine generator is adapted from the IEEE First Benchmark Model (FBM) for computer simulation of sub-synchronous resonance. The data for the HVDC cable transmission are adapted from Control performance on HVDC benchmark models. The modeling aspects of the electromechanical system, consisting of the generator model, mechanical system, the excitation system, power system stabilizer (PSS), and the transmission lines are given in power system dynamics. The strength of the ac systems connected to the terminals of a dc link is measured in terms of effective short-circuit ratio (ESCR) which is defined as

ESCR= (Short Circuit level at the converter bus - Q_c)/ (Rated power)

Where Q_c is the reactive power supplied by the fixed capacitors used at the converter bus for reactive power support (nominal value of Q_c =0.30 p.u)

The analysis is carried out on the test system based on the following initial operating conditions and assumptions.

- The generator delivers 0.125-p.u. power to the transmission system.
- The magnitude of the generator terminal voltage is set at 1.05 p.u.
- The magnitude of the converter bus voltages is set at 1.01 p.u. The magnitudes of both infinite bus voltages are set at 1.0 p.u.
- The VSC1 draws 0.9-p.u. power (P_1) from bus1 to feed to the HVDC cable for rectifier operation. The reactive powers drawn by VSC1 and VSC2 are set to zero (Q_1=Q_2=0), the base megavolt ampere (MVA) is 300 MVA, and the ac voltage base is taken to be 500 kV and the dc voltage base is 150 kV.
- The generator rating is taken to be 300 MVA in all case studies.
- The ESCR of ac system-2 (ESCR2) is fixed at 3 for base cases.

The damping characteristics of the VSC HVDC are dependent on the ac system strength to which it is connected. The strength of the adjacent ac system is changed by varying the line reactance X_{e1}. The variation of the electrical damping torque T_{de} with frequency for cases 1 to 8 is shown in figures

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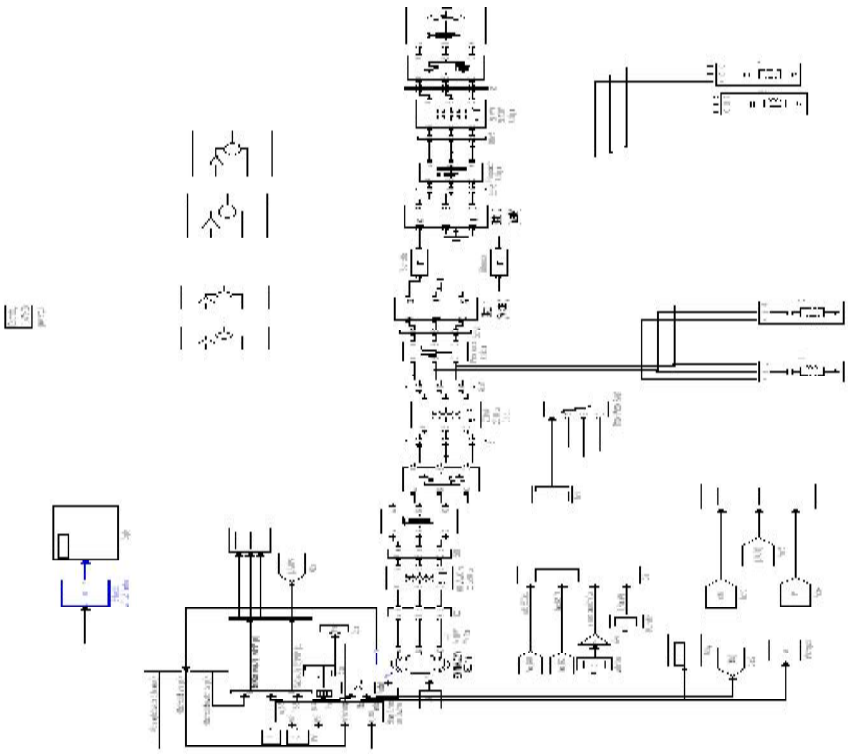
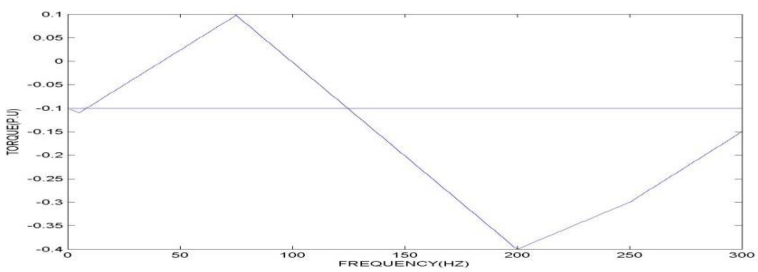
By operating the system for different operating combinations, we can estimate the variation of damping torque with respect to frequency, the controller parameters of the case1 to case8 are given below for mode 0 with ESCR=2.5&4.5 Operating combinations of VSC-based HVDC

MATLAB Model of VSC Based HVDC transmission system



Case 1: VSC1 Rectifier: controller1: Power controller2: Reactive current
VSC2 Inverter:controller1: DC Voltage controller2: Reactive current



Plot of the damping torque with frequency for case1, mode0 with ESCR=2.5&4.5

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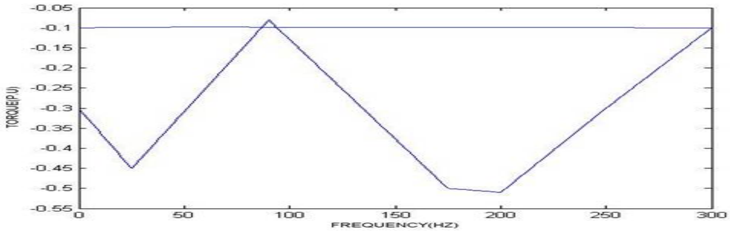
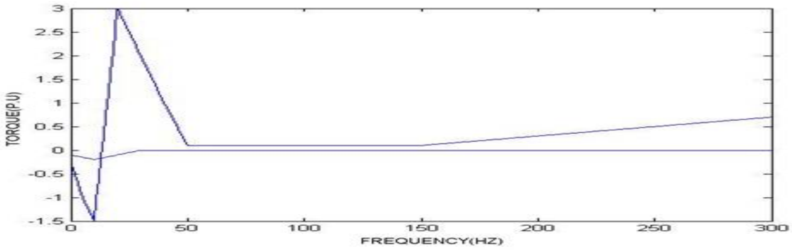
Case 2: VSC1 Rectifier: controller1: Power controller2: AC Bus Voltage
VSC2 Inverter: controller1: DC Voltage controller2: AC Bus Voltage



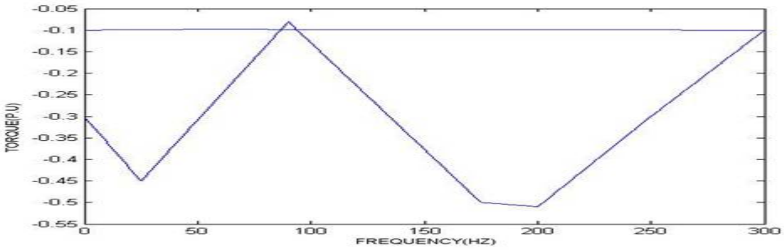
Plot of the damping torque with frequency for case2, mode0 with ESCR=2.5&4.5

Case 3: VSC1 Rectifier: controller1:DC Voltage controller2: Reactive Current
VSC2 Inverter: controller1: Power controller2: Reactive Current



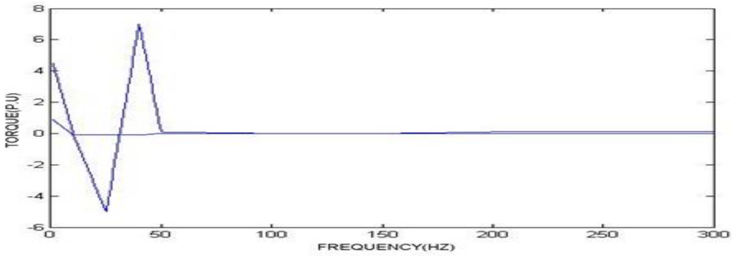
Plot of the damping torque with frequency for case3, mode0 with ESCR=2.5&4.5

Case 4: VSC1 Rectifier: controller1: DC Voltage controller2: Reactive Current
VSC2 Inverter: controller1: Power controller2: Reactive Current



Plot of the damping torque with frequency for case4, mode0 with ESCR=2.5&4.5

Case 5: VSC1 Inverter: controller1: Power controller2: Reactive current
VSC2 Rectifier: controller1: DC Voltage controller2: Reactive current



Plot of the damping torque with frequency for case5, mode0 with ESCR=2.5&4.5

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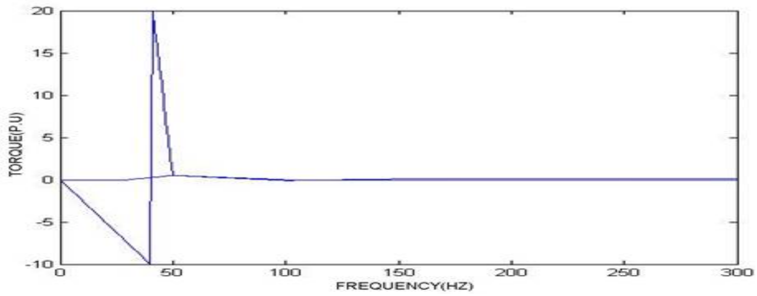
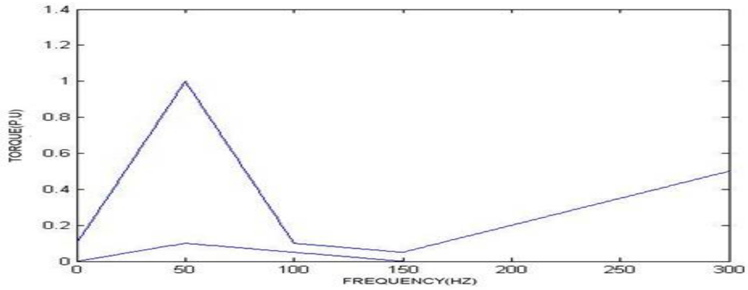
Case 6: VSC1 Inverter: controller1: Power controller2: AC Bus Voltage
VSC2 Rectifier controller1: DC Voltage controller2: AC Bus Voltage



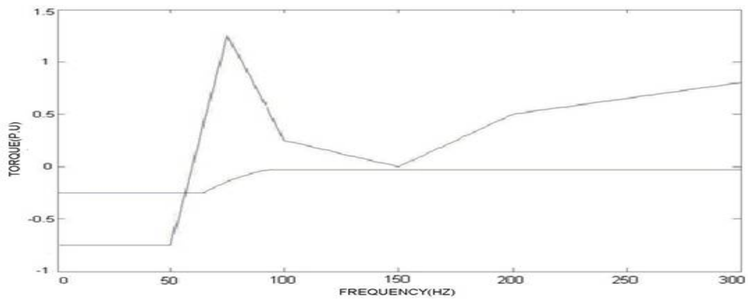
. Plot of the damping torque with frequency for case6, mode0 with ESCR=2.5&4.5

Case 7: VSC1 Inverter: controller1: DC Voltage controller2: Reactive Current
VSC2 Rectifier:controller1: Power controller2: Reactive Current



Plot of the damping torque with frequency for case7, mode0 with ESCR=2.5&4.5

Case 8: VSC1 Inverter: controller1: DC Voltage controller2: AC Bus Voltage
VSC2 Rectifier: controller1: Power controller2: AC Bus Voltage



Plot of the damping torque with frequency for case8, mode0 with ESCR=2.5&4.5

The effect of reduced ac system strength (ESCR=2.5) is to increase the magnitude of the dip in damping torque below w_m=50 rad/s (case 5). The magnitude of the dip in damping torque (negative damping) is more pronounced with ac voltage control when the generator is at inverter (case-6) whereas it reduces the magnitude of this dip (negative damping) when the generator is at rectifier (case-4). Since these frequencies at which the dip occurs do not match with any of the torsional- mode frequencies of IEEE FBM, the system is expected to be stable. It is observed that except for cases 1 and 2 where VSC1 (connected close to the generator) operates as a rectifier in the power control mode, the

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reduction in ESCR improves damping of torsional modes at higher frequencies (w_m>120 rad/sec).The effect of reduction in ac system strength (ESCR=2.5) is to reduce the damping of torsional modes when the generator is at the rectifier (cases 1 and 2) and to increase when the generator is near the inverter (cases 7 and 8).

EIGENVALUE ANALYSIS:

The Eigen value results with a weak ac system (ESCR1=2.5) when the generator is at the rectifier (for cases 1 and 3) are given in Table.

Eigen values of the detailed system with a VSC-based HVDC for ESCR1=2.5

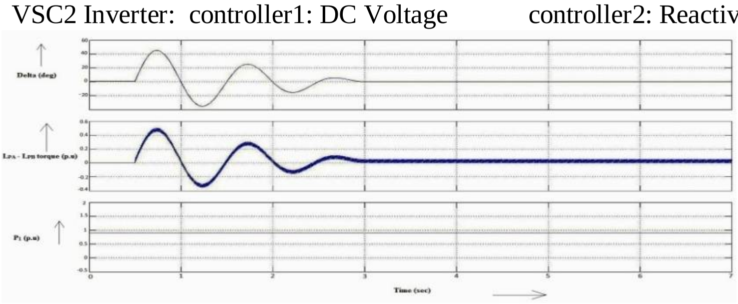
Tor-Mode	Eigen Value				
	Case-1	Case-3	Case-5	Case-6	Case-7
0	-0.490±j6.0132	-0.457±j6.08	-1.152±j5.9	-0.82±j6.131	-0.595±j5.526
1	-0.204±j98.93	-0.235±j98.9	-0.192±j98.89	-0.14±j98.90	-0.27±j98.92
2	-0.0711±j127	-0.0739±j127	-0.0748±j127	-0.0749±j127	-0.0751±j127
3	-0.6234±j160	-0.64±j160.5	-0.623±j160.5	-0.66±j160.5	-0.64±j160.5
4	-0.33±j202.9	-0.34±j202.9	-0.39±j202.9	-0.39±j202.9	-0.37±j202.9
5	-1.85±j298.17	-1.85±j298.1	-1.85±j298.17	-1.85±j298.17	-1.85±j298.17

The above Table shows Eigen values of the detailed system with a VSC-based HVDC for ESCR1=2.5 It is observed that the damping of torsional modes is increased with the dc voltage control mode of the operation of rectifier (case-3) compared to the constant power operation (case-1). These results are in agreement with damping torque results. It also gives the Eigen value results with a weak ac system (ESCR1=2.5) when the generator is at the inverter (for cases 5, 6, and 7). It is observed that although the damping of mode-1 is reduced for case-5 (the inverter is on constant power control) compared to that of case-1 and 3, the damping of other torsional modes (mode 2, 3 and 4) is increased. It is to be noted that, constant ac voltage (case-6) further reduces the damping of mode-1 whereas the damping of other modes increases. The damping of mode-1 is increased when the inverter is on dc voltage control (case-7) compared to constant power control (case-5). Mode 5 is unaffected as its modal inertia is very high. These results are in agreement with damping torque results. In general, the dc voltage control of the VSC close to the generator results in better damping of torsional modes compared to constant power control as well as the three-phase model of the VSC HVDC is carried out using MATLAB-

V. SIMULINK

The controller parameters of the case1 condition are given below

Case1: VSC1 Rectifier: controller1: Power controller2: Reactive current
VSC2 Inverter: controller1: DC Voltage controller2: Reactive current



Variation of the rotor angle, LPA-LPB section torque, and at power at converter1 for a pulse change in Tm(D-Q model) for case-1 with ESCR1=4.5

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VI.CONCLUSION

. In this paper, the analysis and simulation of a VSC-based HVDC system are presented. The various operating modes of the HVDC system are considered for the investigation of possible SSR conditions..The DC voltage control of the VSC (rectifier/inverter) close to generator units causes better damping of SSR . The constant power control of the rectifier situated close to the generator contributes to small negative damping, and the system is stable as the net damping is positive and that of inverter situated close to the generator can destabilize the system in a narrow range of low frequencies. Unlike the LCC-based HVDC (also called "classical HVDC"), the problem with VSC HVDC is minor except under constant power control of the inverter. However, the dc voltage control of the VSC (rectifier/inverter), close to generator units, actually provides small positive damping. Thus, there may be no need to plan a sub-synchronous damping controller (SSDC) for VSC-based HVDC system

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