Indian Journal of Fundamental and Applied Life Sciences ISSN: 2231– 6345 (Online)
An Open Access, Online International Journal Available at www.cibtech.org/sp.ed/jls/2015/01/jls.htm
2015 Vol.5 (S1), pp. 930-936/Rajabi et al.

Research Article

IAGUERRE FUNCTIONS FOR SUPPLEMENTARY DAMPING CONTROLLER DESIGN FOR BTB VSC HVDC

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ABSTRACT
Power systems are large scale systems that are subject to low frequency oscillations. These oscillations degrade the system performance. It is well known that the dynamical stability of the AC system in a composite AC-DC system can be improved by taking advantage of the fast controllability of Voltage Source Converter High Voltage Direct Current (VSC HVDC) converters. In this article a model predictive control (MPC) approach for a VSC HVDC will be presented. This controller is used with input of VSC HVDC to damp low frequency oscillations of power system. Because of having four inputs for VSC HVDC, The potential of inputs to enhance the dynamic stability is evaluated by measuring the electromechanical controllability through singular value decomposition (SVD) analysis. Since model predictive controller is designed based on a mathematical model of the plant, a linearizes model of a power system equipped with VSC HVDC is considered.

Keywords: *System Dynamic Stability, Model Predictive Controller, Singular Value Decomposition (SVD), VSC HVDC.*

INTRODUCTION

Submitted papers Recently VSC HVDC systems have greatly increased. VSC HVDC transmission links are used in power systems for various purposes, for example, interconnecting two neighboring systems of using different frequencies, improving system transient stability, etc. Many existing VSC HVDC control methods provide various forms of modulation for damping power system oscillation and improving dynamic performance (Hsu and Wang, 1988; Badran and Choudhry, 1993; Hao, 1993). Power system stabilizers (PSSs) aid in maintaining power system stability and improving dynamic performance by providing a supplementary signal to the excitation system (Chaturvedi *et al.*, 2004). However, PSSs may adversely affect voltage profile, may result in leading power factor, and may not be able to suppress oscillations resulting from severe disturbances (Ali *et al.*, 2007).

Flexible AC Transmission System (FACTS) controllers, such as Static Var Compensators (SVC), Thyristor Control Series Compensators (TCSC), Static Synchronous Compensators (STATCOM), and Unified Power Flow Controller (UPFC), can be applied to damping oscillations by adding a supplementary signal for main control loops (Wang and Swift, 1997; Yang *et al.*, 1998; Uzunovic *et al.*, 1999).

VSC HVDC systems may improve the transient and dynamic performance of the interconnected AC/DC system due to its fast electronic control of power flow and also the transient stability of the AC systems in a composite AC-DC system can be improved by taking advantage of the fast controllability of VSC HVDC converters (Hammad and Taylor, 1991; Gjerdc *et al.*, 1996; Huang and Krishnaswamy, 2002; Baker *et al.*,).

In this paper a novel approach is presented to model parallel AC/DC power system namely Phillips-Heffron model based d-q algorithm in order to studying system dinamical stability. In addition, a block diagram representation is formed to analyze the system stability characteristics. By this modeling approach, it is possible to analyze the small-signal stability of the system and low-frequency oscillation phenomena which is caused by external disturbances such as variation of input torque and fault occurring. In order to enhance dynamical stability of power system, a supplementary signal which is the same as that applied for FACTS devices, is superimposed on the main input control signals in this paper. To measure the controllability of VSC HVDC supplementary controller by a given input (control signal), the singular value decomposition (SVD) is employed.

Configuration of Power System

Figure 1 shows a SMIB system equipped with a VSC HVDC. As it can be seen the infinite bus is supplied by HVAC parallel connected with an VSC HVDC power transmission system. The VSC HVDC consists of two coupling transformer, two three-phase IGBT based voltage source converters (VSCs). These two converters are connected either back-to-back or joined by a DC cable, depending on the application.

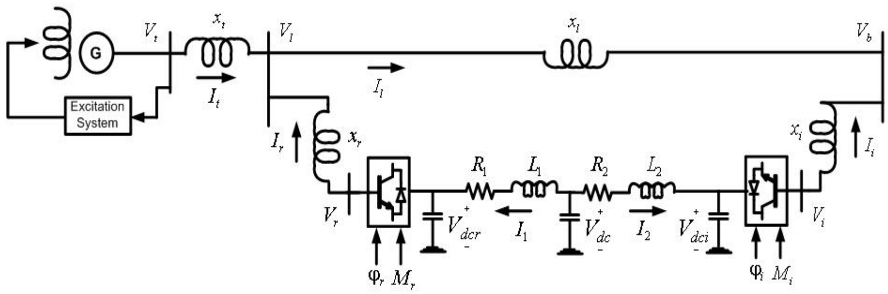

Figure 1: The SMIB system equipped with a VSC HVDC

The AC side of each converter is connected to the line through a coupling transformer. The first voltage source converter behaves as a rectifier. It regulates the DC link voltage and maintains the magnitude of the voltage at the connected terminal.

The second voltage source converter acts as a controlled voltage source, which controls power flow in VSC HVDC feeder. The four input control signals to the VSC HVDC are Mr, PHr, Mi, PHi where Mr Mi are the amplitude modulation ratio and PHr, PHi are phase angle of the control signals of each VSC respectively.

Power System Non-Linear Model

By applying Park's transformation and neglecting the resistance and transients of the coupling transformers, the VSC HVDC can be modeled: Where V_l V_b, I_r and I_i are the middle bus voltage, infinite bus voltage, flowed current to rectifier and inverter respectively. C And V_{dc} are the DC link capacitance and voltage, respectively. C_r, C_i, V_{dcr} and V_{dci} are the DC capacitances and voltages of rectifier and inverter respectively.

The non-linear model of the SMIB system of Figure 1 is:

$$\begin{bmatrix} V_{ld} \\ V_{lq} \end{bmatrix} = \begin{bmatrix} 0 & x_r \\ -x_r & 0 \end{bmatrix} \begin{bmatrix} I_{rd} \\ I_{lrq} \end{bmatrix} + \begin{bmatrix} \dfrac{M_r V_{dcr} \cos(\varphi_r)}{2} \\ \dfrac{M_r V_{dcr} \sin(\varphi_r)}{2} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_{bd} \\ V_{bq} \end{bmatrix} = \begin{bmatrix} 0 & x_i \\ -x_i & 0 \end{bmatrix} \begin{bmatrix} I_{id} \\ I_{iq} \end{bmatrix} + \begin{bmatrix} \dfrac{M_i V_{dci} \cos(\varphi_i)}{2} \\ \dfrac{M_i V_{dci} \sin(\varphi_i)}{2} \end{bmatrix} \quad (2)$$

$$C\dot{V}_{dc} = -(I_1 + I_2) \quad (3)$$

$$L_1 \frac{dI_1}{dt} = V_{dc} - V_{dcr} - R_1 I_1 \quad (4)$$

$$L_2 \frac{dI_2}{dt} = V_{dc} - V_{dci} - R_2 I_2 \quad (5)$$

$$\dot{\delta} = \omega_b(\omega - 1) \quad (6)$$

$$\dot{\omega} = \frac{(P_m - P_e - D\omega)}{M} \quad (7)$$

$$\dot{E}'_q = \frac{(E_{fd} - (x_d - x'_d)I_t - E'_q)}{T'_{do}} \quad (8)$$

$$\dot{E}_{fd} = \frac{(K_A(V_{ref} - V_t + u_{PSS}) - E_{fd})}{T_A} \quad (9)$$

$$P_e = V_{td} I_{td} + V_{tq} I_{tq} \quad (10)$$

By line arising eq (1)-(7), (10)

$$\dot{\Delta\delta} = \omega_b \Delta\omega \quad (11)$$

$$\dot{\Delta\omega} = \frac{(\Delta P_m - \Delta P_e - D\Delta\omega)}{M} \quad (12)$$

$$\dot{\Delta E_q'} = \frac{(\Delta E_{fd} - (x_d - x_d')\Delta I_{td} - \Delta E_q')}{T_{do}'} \quad (13)$$

$$\dot{\Delta E_{fd}} = \frac{(K_A(\Delta V_t + \Delta u_{PSS}) - \Delta E_{fd})}{T_A} \quad (14)$$

$$\Delta V_t = K_6 \Delta E_q' + K_{vdcr}\Delta V_{dcr} + K_{vM_r}\Delta M_r + K_{v\varphi r}\Delta\varphi_r \quad (15)$$

$$\Delta P_e = K_2 \Delta E_q' + K_{pdcr}\Delta V_{dc} + K_{pMr}\Delta M_r + K_{p\varphi r}\Delta\varphi_r \quad (16)$$

$$\Delta E_q = K_4 \Delta\delta + K_{q\varphi r}\Delta\varphi_r + K_{qMr}\Delta M_r + K_{qdcr}\Delta V_{dcr} \quad (17)$$

$$\Delta V_{dcr} = \frac{C_{32}}{C_r}\Delta E_q' + \frac{C_{33}}{C_r}\Delta V_{dcr} + \frac{1}{C_r}\Delta I_1 + \frac{C_{34}}{C_r}\Delta M_r + \frac{C_{35}}{C_r}\Delta\varphi_r \quad (18)$$

Substitute eq(15)-(17) in (11)-(14) we can obtain the state variable of the power system installed with the VSC HVDC to be (state space model): The linearised dynamic model of eq (19) can be shown by Figure 2

$$\dot{X} = AX + BU \quad X = [\Delta\delta, \Delta\omega, \Delta E_q', \Delta E_{fd}, \Delta V_{dcr}, \Delta_{I1}, \Delta V_{dc}, \Delta I_2, \Delta V_{dci}]^T$$
$$U = [\Delta M_r, \Delta\varphi_r, \Delta M_i, \Delta\varphi_i, u_{PSS}]^T \quad (19)$$

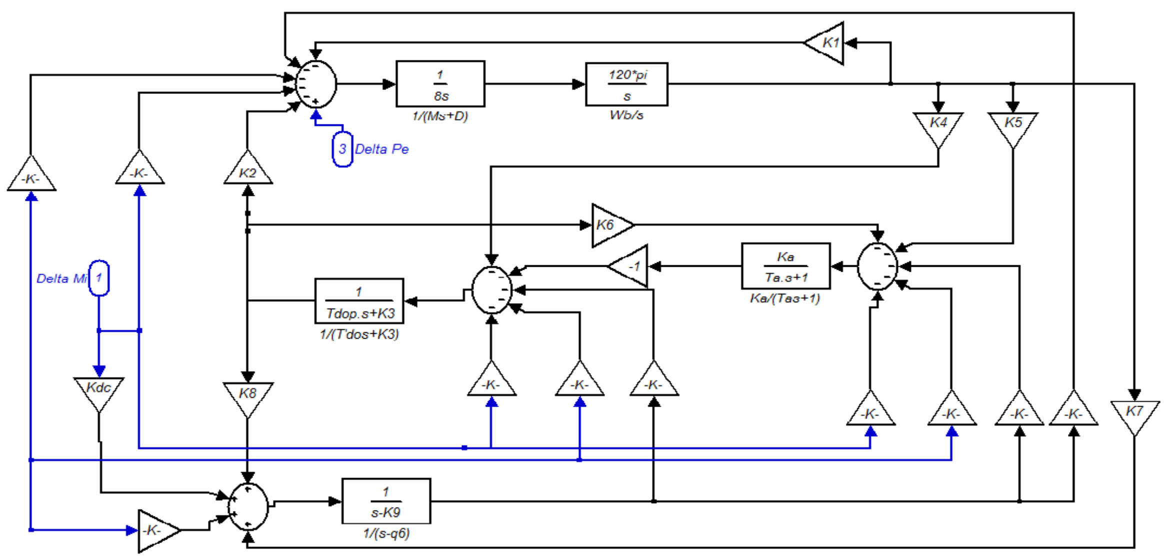

Figure 2: VSC HVDC Block Diagram based eq(19)

Controllability Measure

To measure the controllability of the EM mode by a given input (control signal), the singular value decomposition (SVD) is employed (Huang and Krishnaswamy, 2002). Mathematically, if G is a m*n complex matrix, then there exist unitary matrices U and V with dimensions of m*n and n*n, respectively, such that:

$$G = U\Sigma V^H \quad (20)$$

With

The minimum singular value, $\sigma_{\min}$ of the matrix $[\lambda I - A, h_i]$ indicates the capability of the i_{th} input to control the mode associated with the eigenvalue λ. Actually, the higher $\sigma_{\min}$, the higher the controllability of this mode by the input considered. As such, the controllability of the EM mode can be examined with all inputs in order to identify the most effective one to control the mode.

Design of Damping Controllers

Conventional Lead-Lag Controller

The damping controllers are designed to produce an electrical torque in phase with the speed deviation. The four control parameters of the VSC HVDC (PHr, Mi, PHi) can be modulated in order to produce the damping torque. The speed deviation $\Delta\omega$ is considered as the input to the damping controllers. The structure of VSC HVDC based damping controller is shown in Figure 3. It consists of gain, signal washout and phase compensator blocks. The parameters of the damping controller are obtained using the phase compensation technique (Hammad and Taylor, 1991).

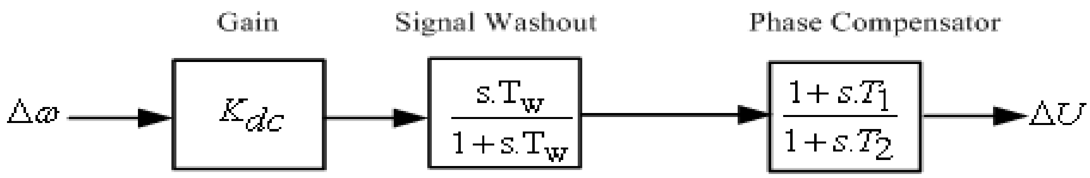

Figure 3: Structure of BtB VSC HVDC based damping controller

Discrete Model Predictive Controller

Assume a plant which is described by:

$$x_m(k+1) = A_m x_m(k) + B_m u(k),$$
$$y(k) = C_m x_m(k), \qquad (21)$$

where u is the manipulated variable or input variable; y is the process output; and xm is the state variable vector with assumed dimension n1. Note that this plant model has u(k) as its input. Thus, we need to change the model to suit our design purpose in which an integrator is embedded. Taking a difference operation on both sides of (21), we obtain that

$$x_m(k+1) - x_m(k) = A_m(x_m(k) - x_m(k-1)) + B_m(u(k) - u(k-1)). \qquad (22)$$

$$x_m(k+1) = A_m x_m(k) + B_m u(k). \qquad (23)$$

Simulation Results

Power system information is given in appendix A. Constant coefficients in (19) are calculated according informations who given in appendix B. For given information, poles of the VSC HVDC system are:

$$-17.0984 + 6.6503i, -17.0984 - 6.6503i, \ -0.1670 + 15.8881i,$$
$$-0.1670 - 15.8881i - 0.0182 + 3.6842i, \ -0.0182 - 3.6842i,$$
$$0.7675 + 2.3900i, \ \ 0.7675 - 2.3900i, \ \ -1.4115$$

According above, there are two poles with positive real part and power system is unstable.

Controllability Measure

SVD is employed to measure the controllability of the electromechanical mode (EM) mode from each of the five inputs: (PHr,Mi,PHi),. The minimum singular value $\sigma_{\min}$ is estimated over a wide range of operating conditions.

For SVD analysis, P_e ranges from 0.01 to 1.5 Pu and Q_e= (-0.3,0.3). At each loading condition, the system model is linearized, the EM mode is identified, and the SVD-based controllability measure is implemented. For comparison purposes, the minimum singular value for all inputs at Q_e=(-0.3,0.3) and 0.3 Pu is shown in Figure 4, respectively.

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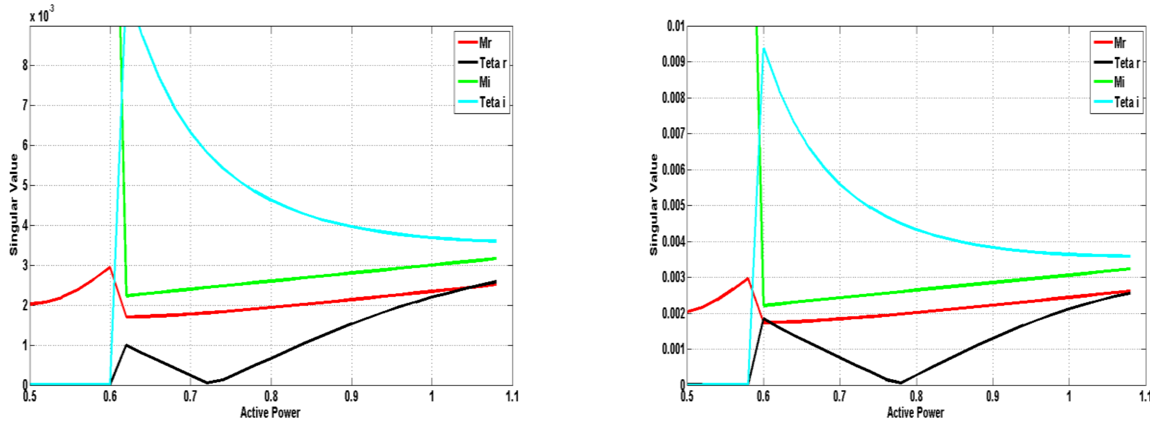


(b) Qe=(0.3) (b) Qe=-(0.3)

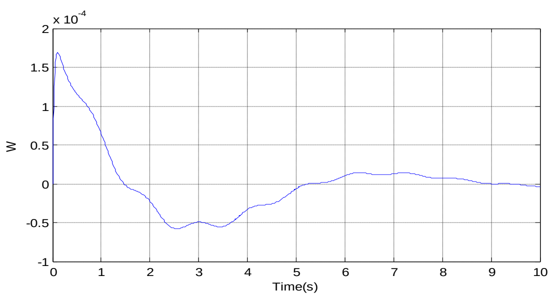
Figure 4: SVD results for five inputs

Testing Proposed Supplementary Controllers

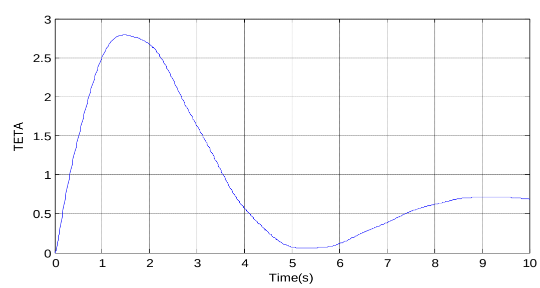
To assess the effectiveness of the proposed stabilizers two different conditions are considered according Table.1. Rotor speed deviation and load angle for suddenly change in input power ($\Delta P_m = 0.1$) at t=3s is shown in Figure 4.

Table 1: Load condition

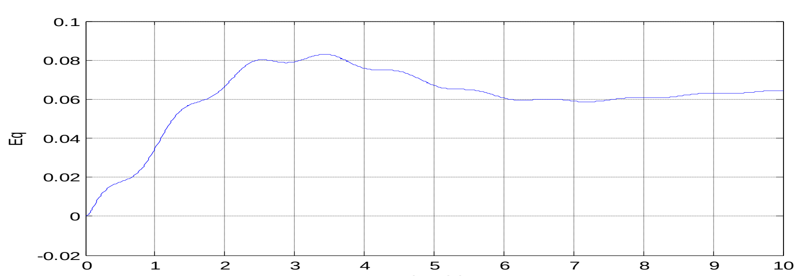
Loading	Pe(pu)	Q_e(pu)
Nominal	0.9	0.1
Heavy	1.1	0.4



Rotor speed deviation

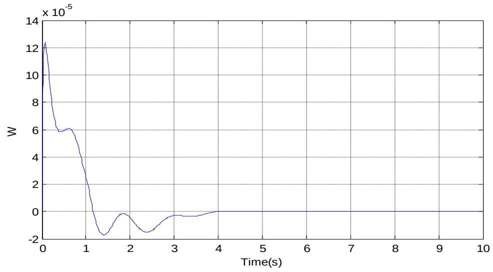


Rotor angle deviation (deg)

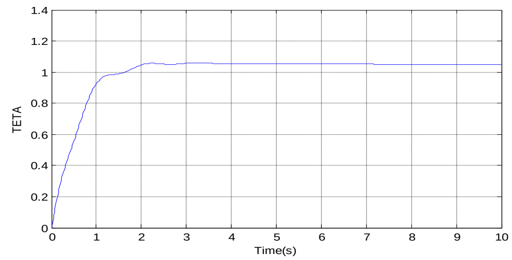


Internal voltage behind transient and synchronous reactances

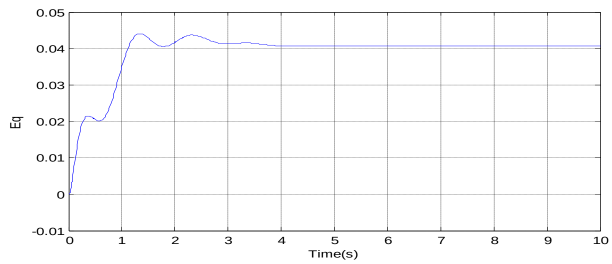
Figure 5: Nominal load results



Rotor speed deviation internal



Rotor angle deviation (deg)



Internal voltage behind transient and synchronous reactances
Figure 6: Heavy load results

Figure 5,6 shows the results of applying mpc controller for HVDC system. It is shown the best damping for rotor speed deviation is abtained using this controller.

CONCLUSIONS

In this paper, a dynamic model based VSC HVDC is considered and a supplementary mpc controller is designed for improve power system stability and oscillation damping. SVD has been employed to evaluate the EM mode controllability to the four VSC HVDC input. SVD illustrated that the EM mode has best controllability via the fire angle of rectifier. Simulation results carried by MATLAB, show the proposed strategy has fast dynamic response

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