A Study of Small Signal Stability of the Power System with VSC Based HVDC Link

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Abstract

The wind power is evacuated using a 5 terminal DC system. Aside from the slack bus, all of the VSC buses' reference powers may be changed to alter the amount of power sent into DC and AC systems. At steady state, the effect of distributing power between an AC and a DC system in varying amounts is examined. When synchronous generators inject power into AC and DC networks, the losses, real and vi reactive power production, and voltage profile of the system are all affected. A real utility system with 156 buses, 209 lines, and wind power-penetrating buses is examined in the above study. A power penetration and load level at different buses and overloading's in transmission lines and transformers are taken into account to establish the topology of two DC rings. The overloading of the AC lines and transformers has been reduced, according to the results of a load flow study. Increases in wind power might be met with the DC ring, opening the door to further capacity. Furthermore, this technology offers a significant advantage: the control of the active power independently of the reactive power. With the use of different modulation techniques, the VSC can independently control the active power flowing through the transmission system as well as the reactive power being exchanged with the connected AC network. Therefore, different types of controllers and strategies can be used depending on the environment chosen for the VSC-HVDC to operate. In this thesis, for the onshore stations the DC voltage control was set for the active channel and the reactive power exchanged with the connected AC network was the control chosen for the reactive channel. On the other hand, at the offshore stations, the controls used were the active power generated at the wind farms for the active channel and the module of the AC voltage at the PCC of the stations for the reactive channel.

Keywords: *Small Signal Stability, Power System, Vsc Based Hvdc Link, wind power, DC system.*

1. INTRODUCTION

In this paper small signal stability of the power system with VSC based HVDC link employing two different control strategies, phase angle control and vector current control are analyzed. Quasi-static analysis is useful only for relatively slow dynamic processes. To analyze faster dynamics, the electromagnetic transient model is vital. The AC network on both sides of the converters (HVDC link) is modelled as thevenin's voltage sources behind the thevenin's impedances viewed from the converter transformer terminal. Dynamic equations of the AC side, the DC side and the controllers are developed. The standard nine-bus system is considered for analysis with a VSC based HVDC link between buses 8 and 9. The network parameters such as short circuit ratios (SCR) at PCC, DC capacitor in the DC link and thevenin's equivalent resistances (system damping) are varied and their effect on the eigenvalues and damping are analyzed.

Over the past years, a number of research publications on investigation of the controller dynamics of VSC-HVDC link were reported. Grid voltage vector orientation based current controllers are accepted as utility standard technology and is widely employed for the control of VSC based HVDC links. The impact of controllers on enhancement of power transfer capability with the SCR less than 1 p.u, is presented by Zhang et al (2010). The effect of poor damping offered by the weak network is overcome by providing a high pass filter. Liu Y et al have shown that dynamic reactive power support during LVRT ride through conditions is achieved by adjusting the active and reactive current references dynamically. Tradeoff is arrived between adjusting real power droop setting and LVRT support without violating device current limitation. Full dynamic insight including the effect of the inner current controllers and the time constants involved in converter power electronics, along with AC-DC interface equations for VSC-MTDC system is given by Jef Breetan et al (2010).

Small signal stability analysis is employed to tune the controller parameters and to mitigate subsynchronous oscillations in hybrid systems. The small signal dynamics of the WTG and SG connected to multiterminal VSC-

HVDC link is presented by Kalcon et al (2012). The state space model of the system is developed and root loci analysis gives the range of controller gain for stable operation.

This work considers VSC DC link which is electrically far away from the SG. Yan et al (2010) have shown that modes corresponding to the Synchronous Generators (SG) are not sensitive to controller gain parameters of Wind Turbine Generator (WTG). Thus power system on either side of the converters is thevinised and connected at the Point of Common Coupling (PCC). Any change in the network topology on either AC sides is reflected on the thevenin impedance seen from the converter AC terminals. The dynamics of the AC system, two terminal DC link and the grid voltage vector orientation based current controllers are modelled. The most critical modes are identified and depending upon the sensitivity of the controller parameters to various modes, a sequential tuning methodology is proposed. Sequential load flow analysis of AC/ DC system is performed to initialize state variables.

2. PHASE ANGLE CONTROL TWO TERMINAL VSC-MTDC SYSTEM

In a grid connected VSC, the phase shift angle, δ and the modulation ratio, M are the two parameters used to control the real power and reactive power respectively. The phase shift angle, δ is the angular difference between V_{pcc} and V_c. It is used to control either the real power flow into or out of VSC fictitious bus or regulate the DC capacitor voltage to maintain the power balance in the inner DC link. The modulation ratio, M is used to regulate the AC bus voltage, V_{pcc}or the reactive power flow between the AC bus and the fictitious VSC bus. By varying δ and M, four quadrant operations of the active power P and the reactive power Q can be obtained. The voltage of the VSC bus can be represented in terms of the DC capacitor voltage u_{dc}, and the PWM modulation ratio, M and the DC voltage usage, μ as

$$V_c = \frac{\mu M u_{dc}}{\sqrt{2}} \quad (1)$$

The power fed into VSC link must be equal to the sum of the power output from the VSC link and the losses. To maintain the power balance condition, if the active power is controlled at the rectifier side, the DC capacitor voltage has to be controlled at the inverter side. The reactive power at the rectifier side and the inverter side can be controlled independently.

Comparison between Phase Angle Control and Power Synchronization Control

One another variation of same phase angle control is reported by Zhang et al (2010) named as power synchronization control. This work reveals the negative impact on the stability of VSC-HVDC link attached to weak AC system due to PLL dynamics. As a solution the power synchronization control is proposed which is achieved by transient power transfer. The dynamic process of a VSC using power-synchronization control is very similar to that of interconnected Synchronous Machines (SM). The transmitted power is increased or decreased by shifting the output voltage phasor of the VSC forwards or backwards. VSC is similar to synchronous source without inertia and controls active power and reactive power independently. This is the simple concept of power synchronization control where PLL can be eliminated. This is in contradictory to vector current control based technology. In vector current control the inner current controller regulates active and reactive power and it can limit the current during the fault conditions. A high pass filter is employed to fictitiously enhance damping of the system. In this chapter simple phase angle control and vector current control are analyzed from small signal stability perspective.

Significance of SCR

Short Circuit Ratio (SCR) is a sensitivity parameter which governs the voltage stiffness with respect to power variations. It is stated as $SCR = \frac{S_{ac}}{P_{dc}}$, where S_{ac} is the short circuit level at the point of common coupling and P_{dc} is the rating of the HVDC link. The short circuit level is inversely proportional to the thevenin equivalent reactance seen at the PCC. The stiffness of the voltage at the PCC depends on the thevenin impedance of the power system.

Mostly wind power is integrated into the power system at subtransmission level. The SCR at the PCC is normally low and is bound to undergo continuous small perturbations when the system topology changes due to operations of breakers. Hence it necessitates the inclusion of network dynamics in the small signal stability analysis.

3. SMALL SIGNAL STABILITY ANALYSIS OF THE POWER SYSTEM WITH VSC BASED HVDC LINK EMPLOYING PHASE ANGLE CONTROL

The single line diagram of the power system with HVDC link is shown in Figure 1. VSC1 and VSC2 are connected to the AC system on either side through transformer impedances. AC system on either side is thevinised looking from the Point of Common Coupling (PCC). Capacitors are connected at PCC. The dynamic equivalent circuit of the VSC based HVDC link is shown in Figure 2.

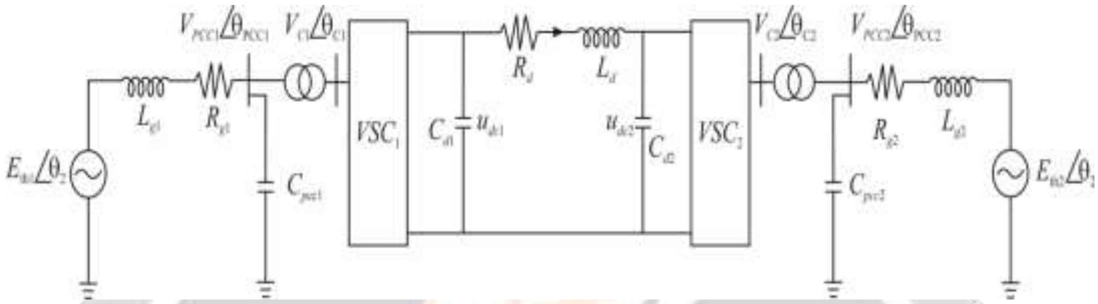

Figure 1 Single line diagram of the power system with VSC based HVDC link

The VSC-HVDC converters are connected to the PCC at bus1 and bus2 respectively as shown in Figure 2. Regulation of active power and the reactive power are considered to be the control objectives of VSC1. Regulating DC link voltage and reactive power are considered to be the control objectives of VSC2. The power system seen from the point of common coupling is thevinised, the thevenin impedance given by R_g + jX_g. Capacitors (C_{pcc}) are connected at the point of common coupling. The impedance of converter transformer is denoted by R_c + jX_c. The voltage at the PCC is given as $V_{pcc}\angle\theta_{pcc}$. The voltage at the fictitious VSC AC bus is denoted by $V_c\angle\theta_c$. The current through the thevenin impedance is denoted by i_g and the current flow in the converter transformer impedance is shown as i_c.

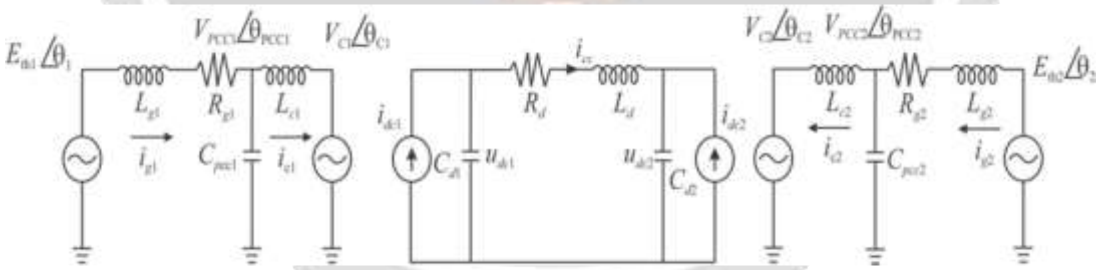

Figure 2 Dynamic equivalent circuit of two terminal VSC based HVDC link

AC System Modelling

The AC side dynamic equations are formulated in synchronous grid dq reference frame with d axis aligned with thevinin equivalent of AC source, E_{th}, adopted by Lidong Zhang et al (2011a & 2011b) and many others. The thevenin voltage of the power system on either side is taken as the reference phasor. This is in contrary to reference phasor adopted in section 4.4 where vector current controller is considered. The grid voltage phasor is taken as the reference. With the convention, d leading q, the q axis resolution of the PCC voltage ceases to exit. Whereas here, in case of phase angle control none of the phasors are rotated.

$$C_{pcc}\frac{dV_{pcc}}{dt} = i_c - i_g \tag{2}$$

$$L_g \frac{di_g}{dt} = V_{pcc} - E_{th} - R_g\, i_g \qquad (3)$$

$$L_c \frac{di_c}{dt} = V_c - V_{pcc} - R_c\, i_c \qquad (4)$$

Equation (1) in dq component form is.

$$C_{pcc} \frac{dV_{pcc}^d}{dt} = i_c^d - i_g^d - \omega C_{pcc} V_{pcc}^q \qquad (5)$$

$$C_{pcc} \frac{dV_{pcc}^q}{dt} = i_c^q - i_g^q + \omega C_{pcc} V_{pcc}^d \qquad (6)$$

$$L_g \frac{d\Delta i_g^d}{dt} = -R_g i_g^d - \omega L_g i_g^q + V_{pcc}^d - E_{th} \qquad (4.7)$$

$$L_g \frac{d\Delta i_g^q}{dt} = -R_g i_g^q + \omega L_g i_g^d + V_{pcc}^q \qquad (8)$$

$$L_c \frac{d\Delta i_c^d}{dt} = -R_c \Delta i_c^d - \omega L_c i_c^q + \left(V_c^d - V_{pcc}^d\right) \qquad (9)$$

$$L_c \frac{d\Delta i_c^q}{dt} = -R_c \Delta i_c^q + \omega L_c i_c^d + \left(V_c^q - V_{pcc}^q\right) \qquad (10)$$

Transformer impedance is considered to be purely reactive, $R_c = 0$. Power system considered is stiff on either sides, $\Delta E_{th} = 0$. Linearised network equations are,

$$\frac{d\Delta V_{pcc}^d}{dt} = \frac{1}{C_{pcc}} \Delta i_c^d - \frac{1}{C_{pcc}} \Delta i_g^d - \omega \Delta V_{pcc}^q \qquad (11)$$

$$\frac{d\Delta V_{pcc}^{q}}{dt} = \frac{1}{C_{pcc}}\Delta i_c^q - \frac{1}{C_{pcc}}\Delta i_g^q + \omega\Delta V_{pcc}^{d} \quad (12)$$

$$\frac{d\Delta i_g^d}{dt} = -\frac{R_g}{L_g}\Delta i_g^d - \omega\Delta i_g^q + \frac{1}{L_g}\Delta V_{pcc}^{d} \quad (13)$$

$$\frac{d\Delta i_g^q}{dt} = -\frac{R_g}{L_g}\Delta i_g^q - \omega\Delta i_g^d + \frac{1}{L_g}\Delta V_{pcc}^{q} \quad (14)$$

$$\frac{d\Delta i_c^d}{dt} = -\omega L_c i_c^q + \frac{1}{L_c}\left(\Delta V_c^d - \Delta V_{pcc}^{d}\right) \quad (15)$$

$$\frac{d\Delta i_c^q}{dt} = +\omega L_c i_c^d + \frac{1}{L_c}\left(\Delta V_c^q - \Delta V_{pcc}^{q}\right) \quad (16)$$

Similarly linearised equations in dq component form are considered for the inverter side. The initial operating point is obtained from load flow studies. The state variables of AC system are given below:

$$\Delta\dot{I}_{c1d}, \Delta\dot{I}_{c1q}, \Delta\dot{V}_{pcc1d}, \Delta\dot{V}_{pcc1q}, \Delta\dot{I}_{g1d}, \Delta\dot{I}_{g1q},$$

$$\Delta\dot{I}_{c2d}, \Delta\dot{I}_{c2q}, \Delta\dot{V}_{pcc2d}, \Delta\dot{V}_{pcc2q}, \Delta\dot{I}_{g2d}, \Delta\dot{I}_{g2q}$$

DC System Modelling

Simplified DC link is included in Figure 4.1.The DC current source in parallel with DC capacitor C_{dc}, and the DC cables represented by the resistance and the inductance of the DC link, form the π model of the DC circuit. The equivalent current injections by the VSC on rectifier and inverter ends are viewed as current sources i_{dc1} and i_{dc2}. The dynamic equations of the DC link current i_{cc} and DC capacitor voltages u_{dc1} and $u_{dc2}$are given by

$$C_{dc}\frac{du_{dc1}}{dt} = i_{dc1} - i_{cc} \quad (17)$$

$$C_{dc}\frac{du_{dc2}}{dt} = i_{dc2} + i_{cc} \quad (18)$$

$$L_{dc}\frac{di_{cc}}{dt} = u_{dc1} - u_{dc2} - R_{dc}i_{cc} \quad (19)$$

The linearised DC link equations are

$$\frac{d\Delta u_{dc1}}{dt} = -\frac{\Delta i_{cc}}{C_{dc}} \quad (20)$$

$$\frac{d\Delta u_{dc2}}{dt} = \frac{\Delta i_{dc2}}{C_{dc}} + \frac{\Delta i_{cc}}{C_{dc}} \qquad (21)$$

$$\frac{d\Delta i_{cc}}{dt} = \frac{\Delta u_{dc1}}{L_{dc}} - \frac{\Delta u_{dc2}}{L_{dc}} - \frac{R_{dc}\Delta i_{cc}}{L_{dc}} \qquad (22)$$

Controller Modelling

In a grid connected VSC, the phase shift angle, δ and the modulation ratio, M are the two parameters used to control the real power and reactive power respectively. The phase shift angle, δ is the angular difference between V_{pcc} and V_c. It is used to control either the real power flow into or out of VSC fictitious bus or regulate the DC capacitor voltage to maintain the power balance in the inner DC link. The modulation ratio, M is used to regulate either the AC bus voltage, V_{pcc} or the reactive power flow between the AC bus and the fictitious VSC AC bus. By varying δ and M, four quadrant operations of the active power P and the reactive power Q can be obtained.

The overall control diagram of the VSC based HVDC with phase angle control is shown in Figure 3. In a grid connected VSC, the phase shift angle, δ and the modulation ratio, M are the two parameters used to control the real power and reactive power respectively. In phase angle control strategy the active power is controlled by phase angle shift between the VSC AC bus and PCC bus. Reactive power is controlled by the voltage magnitude difference between PCC and VSC AC bus voltages. In this control strategy, four PI controllers are employed. The active power and the reactive power are controlled at the rectifier side. The DC capacitor voltage and the VSC AC bus voltage are controlled at the inverter side. The state space model of the controllers is developed in the next section.

The active power controller employed in rectifier side is shown in Figure 4.4. K_P and T_P are the gain and time constant of the active power controller.

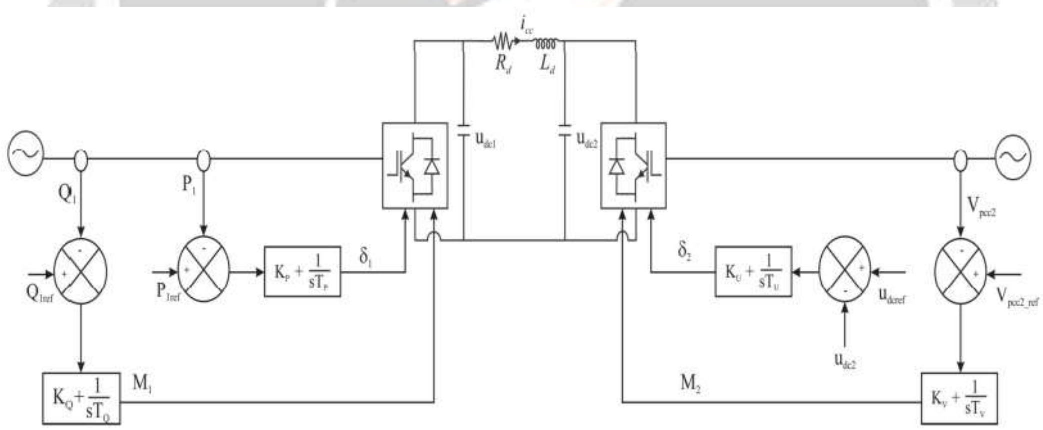

Figure 3: Overall control diagram of VSC based HVDC link with Phase Angle Control

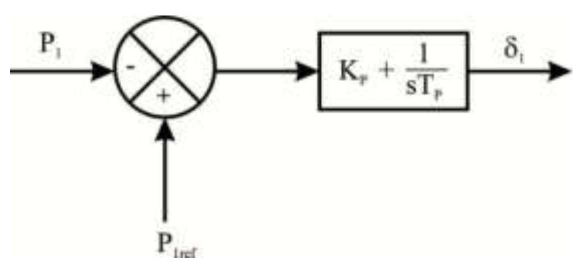

Figure 4: Active Power Controller

From Figure 4, the phase angle shift, δ_1 is

$$\delta_1 = \left(P_{1ref} - P_1\right)\left(k_P + \frac{1}{sT_P}\right) \tag{23}$$

Equation (23) is linearized around the initial operating point δ_{10}. The derivations of linearized dynamic equations are given.

$$\Delta\dot{\delta}_1 = -\frac{V_{pcc}V_c\cos\delta_{10}}{T_P\left(X_{c1} + k_P V_{pcc}V_c\cos\delta_{10}\right)}\Delta\delta_1 \tag{24}$$

The reactive power controller employed in rectifier side is shown in Figure 5. K_Q and T_Q are the gain and time constant of the reactive power controller.

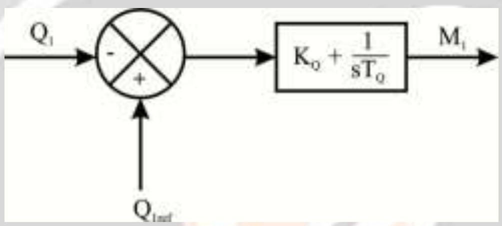

Figure 5 Reactive power controller

From Figure 5, the modulation ratio, M_1 can be calculated as

$$M_1 = \left(Q_{1ref} - Q_1\right)\left(K_Q + \frac{1}{sT_Q}\right) \tag{25}$$

Equation (24) is linearized around the initial operating point M_{10}.

$$\Delta\dot{M}_1 = -\frac{V_{pcc1}k_2\cos\delta_{10} - 2k_2^2 M_{10}}{T_Q\left(X_{c1} + V_{pcc}k_2 K_Q\cos\delta_{10} - 2k_2^2 K_Q M_{10}\right)}\Delta M_1 \tag{26}$$

The DC voltage controller employed in inverter side is shown in Figure 6. K_U and T_U are the gain and time constant of the DC voltage controller.

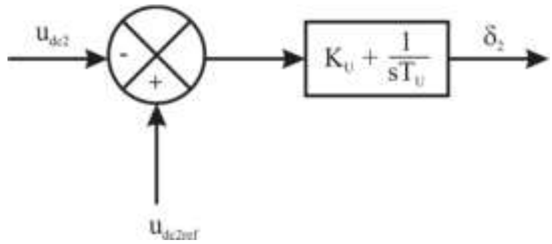

Figure 6 DC voltage controller

4. CONCLUSION

A model of a three-terminal VSC-HVDC system is presented in this thesis. The vector control strategy is described and implemented in PSCAD/EMTDC. The simulation results has shown that operation of M-VSC-HVDC is possible with one VSC terminal regulating the DC voltage while the others converters control the active power flow independently and bi-directionally. The region of controllability as a function of power flow is a very important from the stability point of view. The region of controllability is the region of stability. Hence, the region of controllability ensures that the system is stable as long as the converter rating power is considered. Furthermore, the steady-state and dynamic response characteristics as a function of capacitor size have been investigated. From the simulation results, it is concluded that the active power controller has a fast response for a step change in the input reference, and the DC voltage has almost no ripple if the capacitor size is relatively large. However, the active power controller response is improved when the capacitor size is decreased. Although a smaller capacitor size provides faster response, there is a limitation in choosing a smaller size of capacitor as it will affect the dynamic operation of the HVDC system. Thus, a smaller size of capacitor means high ripple voltage at the DC side.

5. REFERENCES

1. Wenjuan Du et al (2017) “Small-signal stability analysis of integrated VSC-based DC/AC power systems – A review”, International Journal of Electrical Power & Energy Systems > 2017 > 103 > C > 545-552
2. Maturi Lakshmi Chandana (2016) “VSC-HVDC BASED MULTI-TERMINAL SYSTEM TRANSIENT STABILITY ENCHANCEMENT BY USING SWING EQUATION”, IJARIIE-ISSN(O)-2395-4396, Vol-4 Issue-4 2016
3. Jiang, D.; Zheng, H. Research Status and Developing Prospect of DC Distribution Network. Autom. Electr. Power Syst. 2012, 36, 98–104.
4. Yiwen Fan, Yongning Chi, Yan Li, Zhibing Wang, Hongzhi Liu, Wei Liu, Xiangyu Li, Key technologies for medium and low voltage DC distribution system, Global Energy Interconnection, Volume 4, Issue 1, 2016, Pages 91-103, ISSN 2096-5117.
5. Luo, Y.; Li, Y.; Wang, P. DC Voltage Adaptive Droop Control of Multi-Terminal HVDC Systems. Proc. CSEE 2016, 36, 919–2599
6. Lv, Z.; Zhou, M.; Wang, Q.; Hu, W. Small-Signal Stability Analysis for Multi-Terminal LVDC Distribution Network Based on Distributed Secondary Control Strategy. Electronics 2017, 10, 1575. https://doi.org/10.3390/electronics1013157.