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Multi-task control for VSC–HVDC power and frequency control

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ABSTRACT

A robust control strategy for a VSC–HVDC transmission scheme between two ac networks is presented. The VSC converters at both ends of the dc line are equipped with a multi-task controller that facilitates: power management between the two ac systems, provision of independent reactive power control at the point of common couplings (PCCs) and frequency regulation at the sending-end side. The paper investigate the utilization of VSC–HVDC system to provide frequency regulation to an ac network; this is useful for networks with high penetration of renewables (e.g. wind), and nuclear generation. The proposed control strategies for the VSCs are presented in detail, investigating further the tuning method for the proper operation of the inner controllers. The robustness of the control system is tested under large disturbances. The study is conducted in Matlab/Simulink and results that substantiate the dynamic performance of the VSC–HVDC with the proposed control are thoroughly discussed.

1. Introduction

High-voltage dc transmission systems based on voltage source converters (VSC–HVDC) use switching devices such IGBTs or GTOs which can be turned ON and OFF at any time (using pulse width modulation, PWM), increasing control flexibility and capabilities, such independent active and reactive power flow control. Also, with PWM the converter harmonics are those associated with the PWM switching frequency, typically between 1 and 2 kHz [1,2]. In addition, the VSC can provide four-quadrant power controllability. The reactive power exchange between the VSC converter and the ac system can be controlled to provide greater flexibility for the AC system, such as stabilizing a particular bus voltage and operating at unity power factor to minimize the transmission current and reduce the transmission losses [3,4]. All these features have made of VSC–HVDC systems an attractive solution for various applications in power systems (not previously considered due to technical and economical limitations) such as the following [5,6]:

- Integration of large offshore wind farms located far away from shore.
- Connection of weak and isolated areas.
- Development of multi-terminal DC networks.
- Provision of independent reactive power control.

In this paper, a robust controller is developed to equip a VSC–HVDC transmission with multi-task functionality providing power management, frequency regulation and dynamic voltage control at the point of connection. Transient system stability and the improvement in Fault Ride-Through capability is investigated during both ac faults at the receiving end and dc faults at the middle of the dc link.

2. Modeling of the VSC–HVDC test system

The VSC–HVDC transmission test system is shown in Fig. 1 with parameters given in Appendix A. The VSCs have been modeled as three-level NPC converters. Generation in the ac networks has been modeled by synchronous generators with AVR and turbine-governor control. The coupling transformers condition the ac network voltage to a suitable level for the converter, and provide a reactance between the converter and the ac busbar to limit and control the ac current. Three-phase reactors are used to facilitate active and reactive power flow control.

Applying Kirchhoff Voltage Law to the system in Fig. 1, with time t in seconds and all other quantities in per unit, the dynamic equations for VSC_1 converter are [8,9]:

$$\frac{di_{sabc1}}{dt} = -\frac{R_1}{L_1} i_{sabc1} + \frac{1}{L_1}(v_{sabc1} - v_{cabc1}) \quad (1)$$

where $R_1 = R_{T1} + R_{F1}$ and $L_1 = L_{T1} + L_{F1}$.

To simplify the design of the control system, the three-phase quantities are expressed in the dq reference frame using the Park transformation matrix given in Eq. (2) as:

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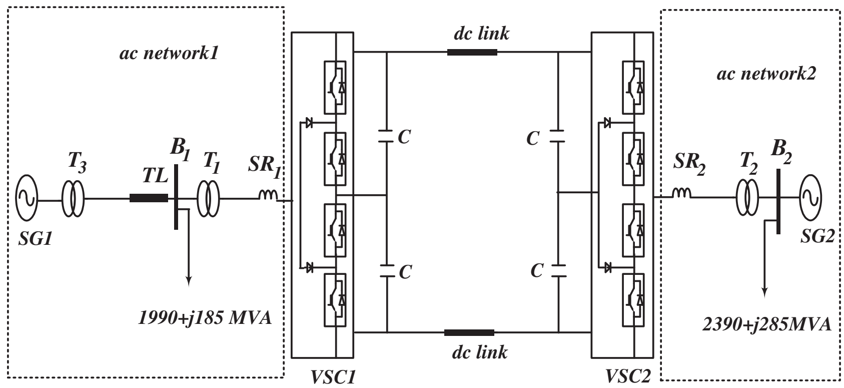

Fig. 1. VSC–HVDC transmission test system.

$$\begin{bmatrix} f_d \\ f_q \\ f_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta-\frac{4\pi}{3}\right) \\ \sin\theta & \sin\left(\theta-\frac{2\pi}{3}\right) & \sin\left(\theta-\frac{4\pi}{3}\right) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} f_b \\ f_b \\ f_c \end{bmatrix} \tag{2}$$

Applying Park's transformation to Eq. (1) the differential equations for VSC_1 in dq coordinates are [10,11]:

$$\frac{di_{sdq1}}{dt} = -\frac{R_1}{L_1}i_{sdq1} + \frac{[V_{sdq1} - V_{cdq1} - j\omega L i_{sdq1}]}{L_1} \tag{3a}$$

The power balance equation between the dc and ac sides in VSC_1 is:

$$\frac{dV_{dc1}}{dt} = \frac{\frac{3}{2}(v_{cd1}\cdot i_{sd1} + v_{cq1}\cdot i_{sq1})}{C\cdot V_{dc1}} - \frac{I_{dc}}{C} \tag{3b}$$

Similarly, the dynamic equations of the inverter-side converter (VSC_2) are:

$$\frac{di_{sdq2}}{dt} = -\frac{R_2}{L_2}i_{sdq2} + \frac{[V_{cdq2} - V_{sdq2} + j\omega L i_{sdq2}]}{L_2} \tag{4a}$$

$$\frac{dV_{dc2}}{dt} = \frac{-\frac{3}{2}(v_{cd2}\cdot i_{sd2} + v_{cq2}\cdot i_{sq2})}{C\cdot V_{dc2}} + \frac{I_{dc}}{C} \tag{4b}$$

In a converter with sinusoidal PWM, the relationship between the modulation index M, dc link voltage and the dq components of the ac voltage at the converter terminals is given by [12,13]:

$$v_{cd} + jv_{cq} = \frac{1}{2}MV_{dc}[cos\delta + jsin\delta] \tag{5}$$

3. Control system strategy

The main function of the VSC is to generate a fundamental-frequency ac voltage from a dc voltage, and to control the generated voltage in phase and magnitude. Vector control, typically used to control the VSC–HVDC, consists of inner and outer controllers. The function of the inner controller is to regulate the current such that it follows the references provided by the outer controllers, and to ensure that the converter is not overloaded during major disturbances. The outer controller is responsible for supplying references values to the inner controller. There are four possible control modes to choose from for the outer controller: constant dc voltage, constant dc power, constant ac voltage, and variable frequency control modes. The choice of the outer controller mode depends on the application of the VSC–HVDC. The dc voltage controller regulates the dc link voltages to ensure the power balance between the sending- and receiving-end converters. In order to design an inner current controller, the cross-coupling terms in Eq. (3) need to be decoupled as follow [10,11]:

$$u_{dq1} = v_{sdq1} - v_{cdq1} + j\omega L i_{dq1} \tag{6}$$

By substituting Eqs. (6) in (1), then

$$\frac{d}{dt}\begin{bmatrix} i_{sd1} \\ i_{sq1} \end{bmatrix} = \begin{bmatrix} -R_1/L_1 & 0 \\ 0 & -R_1/L_1 \end{bmatrix}\begin{bmatrix} i_{sd1} \\ i_{sq1} \end{bmatrix} + \begin{bmatrix} 1/L_1 & 0 \\ 0 & 1/L_1 \end{bmatrix}\begin{bmatrix} u_{d1} \\ u_{q1} \end{bmatrix} \tag{7}$$

where $u_{dq1} = u_{d1} + ju_{q1}$, $i_{dq1} = i_{d1} + ji_{q1}$, $v_{sdq1} = v_{sd1} + jv_{sq1}$ and $v_{cdq1} = v_{cd1} + jv_{cq1}$.

The variables u_{dq1} are new control variables obtained from PI controllers which regulate the dq-axis currents. The values of u_{dq} are defined as:

$$u_{dq1} = k_{pi}(i^*_{sdq1} - i_{sdq1}) + k_{ii}\int(i^*_{sdq1} - i_{sdq1})dt \tag{8}$$

where k_{pi} and k_{ii} are the proportional and integral gains of the current controller, and the superscript * refers to the reference value.

Replacing the integral part of Eq. (8) by new auxiliary control variables z_{dq1} (where $z_{dq1} = z_{d1} + jz_{q1}$), the following set of equations is obtained:

$$u_{dq1} = k_{pi}(i^*_{sdq1} - i_{sdq1}) + k_{ii}z_{dq1} \tag{9}$$

$$\frac{dz_{dq1}}{dt} = -i_{dq1} + i^*_{dq1} \tag{10}$$

Substituting Eqs. (9) in (7) then

$$\frac{d}{dt}\begin{bmatrix} i_{sd1} \\ z_{d1} \\ i_{sq1} \\ z_{q1} \end{bmatrix} = \begin{bmatrix} -(R_1+k_{pi})/L_1 & K_{ii}/L_1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & -(R_1+k_{pi})/L_1 & K_{ii}/L_1 \\ 0 & 0 & -1 & 0 \end{bmatrix}\begin{bmatrix} i_{sd1} \\ z_{d1} \\ i_{sq1} \\ z_{q1} \end{bmatrix} + \begin{bmatrix} k_{pi}/L_1 & 0 \\ 1 & 0 \\ 0 & k_{pi}/L_1 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} i^*_{sd1} \\ i^*_{sq1} \end{bmatrix} \tag{11}$$

From Eq. (11), the dq-currents are defined in the Laplace domain as follow:

$$\begin{bmatrix} i_{sd1}(s) \\ z_{d1}(s) \\ i_{sq1}(s) \\ z_{q1}(s) \end{bmatrix} = \frac{1}{s^2 + \frac{(R_1+K_{pi})}{L_1}s + \frac{K_{ii}}{L_1}}\begin{bmatrix} s & K_{ii}/L_1 & 0 & 0 \\ -1 & s+(R_1+K_{pi})/L_1 & 0 & 0 \\ 0 & 0 & s & K_{ii}/L_1 \\ 0 & 0 & -1 & s+(R_1+K_{pi})/L_1 \end{bmatrix}\begin{bmatrix} i^*_{sd1} \\ i^*_{sq1} \end{bmatrix} \tag{12}$$

Therefore, the Laplace transfer function of the inner (current) controller is: