MODELLING AND CONTROLLER DESIGN FOR VSC-HVDC ATTACHED TO AN AC NETWORK

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Key words: Power System Control, Modelling, Validation

Abstract

In this paper a model and a controller design method for controlling the power and line voltage of a voltage source converter (VSC) in VSC HVDC (High Voltage Direct Current Transmission) attached to an AC system are introduced. The control structure proposed consists of a cascade from power and AC voltage onto a VSC current controller. The controller for the VSC current loop is designed using a standard low order model and the power and voltage controllers are designed using a model extended to included power and AC voltage behaviour. A good validation of the extended model against a rigorous PSCAD model is demonstrated for SCR=4.0 .

1 Introduction

Voltage Source Converter based HVDC (VSC-HVDC) has attracted significant interest since the development of high speed, high voltage switches which enable the advantages of VSC HVDC to be exploited commercially [12] [1] [4]. A number of methods for designing controllers for converter currents using analytical models have been described, the most common being the use of decouplers with a linearising control structure [8][14][6]. Nonlinear methods [15], LQR and H_∞ methods have also been applied [7]. However, the issues associated with controlling power flow and line voltage for non-infinite AC systems have not been directly addressed. The main contributions of this paper are the introduction of a modelling approach and a controller design methodology to deal with the non-linearities introduced by requirements to control AC system power flow and line voltage.

The paper is organised as follows. The standard VSC model, controller structure and VSC current controller design as applied to HVDC are first summarised. The extension of the standard model to include power and line voltage is then described. Finally a power and voltage controller is designed and validated against the rigorous PSCAD model.

Throughout the paper, 3 phase signals are transformed using the 'Park Transformation' into a two phase dq representation in a rotating reference frame, and 'per unit' notation is used [5].

2 VSC HVDC Equivalent Circuit

An equivalent circuit for the power controlling terminal of a VSC HVDC system is shown on Figure 1. The model developed here, extended to include the behaviour of the DC line as described in [14] and [10], may also be used for design of the voltage controlling terminal of a VSC HVDC system.

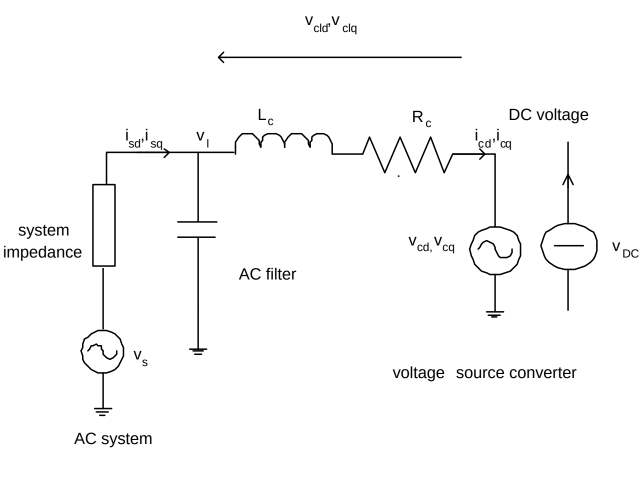

Figure 1: VSC HVDC terminal

3 Linearisation of the Internal VSC Controls

The two 'internal' controls of a VSC controlled by pulse width modulation (PWM) are the phase angle δ of the VSC voltage relative to the point of phase measurement, and the modulation index m, i.e. the ratio between the AC voltage and DC voltage magnitudes [2]. These control signals vary a PWM pattern to provide an AC voltage waveform with magnitude $m.v_{DC}$ and phase δ. Referring to Figure 1, the equations representing a single VSC operation may be written as the following linear system, with inputs v_{cld} and v_{clq} and outputs i_{cd} and i_{cq}:

$$\begin{aligned} \frac{d}{dt} i_{cd} &= -\frac{R_c}{L_c} i_{cd} + \omega i_{cq} - \frac{1}{L_c} v_{cld} \\ \frac{d}{dt} i_{cq} &= -\frac{R_c}{L_c} i_{cq} - \omega i_{cd} - \frac{1}{L_c} v_{clq}, \end{aligned} \quad (1)$$

where

$$v_{cd} = m\, v_{DC} \cos\delta - v_l \qquad v_{cq} = m\, v_{DC} \sin\delta \quad (2)$$

To linearise the VSC behaviour, the internal VSC controls δ and m are set as non-linear functions of the required input voltages v_{cld}, v_{clq} and the measurements v_l (the AC line voltage) and v_{DC}:

$$\delta = \arctan(\frac{v_{cld} + v_l}{v_{clq}}) \qquad m = \frac{v_{clq}}{v_{DC}} \sin\delta \quad (3)$$

4 Control design for the VSC

With the linearising inputs v_{cld}, v_{clq} it is possible to design a current controller for the VSC using linear control techniques. Two approaches to control design are detailed in [3] and summarised below.

In the decoupling design approach introduced in [11], the d and q equations are decoupled, enabling two controllers to be designed using SISO techniques.

LQR is an alternative to decoupled design that is applicable to this system because of the availability of the system states i_{cd} and i_{cq}; it is an attractive approach because of its inherent robustness properties [13]. To provide integral action the system is augmented by integrated states as shown in Figure 2, leading to a 4 input, 2 output static feedback controller.

The validity of the linearised model when the VSC is attached to an AC system with SCR> 4 is detailed in [3]. The simple model and the LQR controller are thus considered to be an appropriate slave model for use in the design of power and line voltage controllers, at least for SCR greater than 4.0.

5 Control Structure for Control of AC Power Flow and AC Line Voltage

The independence from v_l of control using v_{cld} and v_{clq} within the standard VSC model leads to dynamic behaviour of the VSC itself being independent of AC system impedance, and hence AC system strength and SCR [5]. It is therefore proposed to carry out the control design in two stages, leading to a cascade structure for control of power and line voltage using VSC currents. In this structure the objectives of the 'slave' controller are to control converter currents to setpoint, attenuate harmonic disturbances from the VSC, and be robust to unmodelled dynamics effects in the VSC. The objectives of the 'master' controller are to control power and voltage to setpoint, and to be robust to changes in AC system characteristics.

6 Modelling and Control of AC Network

6.1 Model of VSC Attached to a Non-Infinite AC System

When a VSC with linearising control structure as described in section 3 is attached to a non-infinite AC system, the VSC equations (1) still hold. The behaviour of the system between the ideal AC source and the line voltage as shown on Figure 1 is described by the following equations:

$$\begin{aligned} \frac{d}{dt} i_{sd} &= -\frac{R_s}{L_s} i_{sd} + \omega i_{sq} + \frac{1}{L_c}(v_s \cos\delta_s - V_L) \\ \frac{d}{dt} i_{sq} &= -\frac{R_c}{L_c} i_{sq} - \omega i_{sd} - \frac{1}{L_c}(v_s \sin\delta_s) \end{aligned} \quad (4)$$

As in Equation(1) , the reference phasor for dq transforms is the line voltage. The AC source has a voltage magnitude V_s and the angle δ_s of this voltage relative to the line varies as the current flow between the source and the converter changes.

The AC filters required for VSC HVDC are smaller than those required for conventional HVDC and the filter currents are anticipated to be relatively small in the desired operational bandwidth of the VSC (up to 100 Hz). If the filter currents are not considered, i_{sd} and i_{sq} are identical to i_{cd} and i_{cq} respectively in equations 1 and 4, and the derivative terms may be eliminated from these two systems of equations. By elimination of δ_s the AC line voltage can then be expressed as a nonlinear function of $i_{cd}, i_{cq}, v_{cd}, v_{cq}$, the outputs of the slave system, and the system impedance (L_s and R_s).

$$\begin{aligned} v_l =& \frac{i_{cd} L_s R_c}{L_c} - i_{cd} R_s + \frac{L_s v_{cld}}{L_c} \\ &+ v_s \sqrt{1 - \frac{(-i_{cq}\, L_s\, R_c + i_{cq} L_c\, R_s - L_s\, v_{clq})^2}{L_c^2 v_s^2}} \end{aligned} \quad (5)$$

$$P = v_l i_{cd}$$

The transfer function from i_{spd} and i_{spq} to P and v_l can be summarised as:

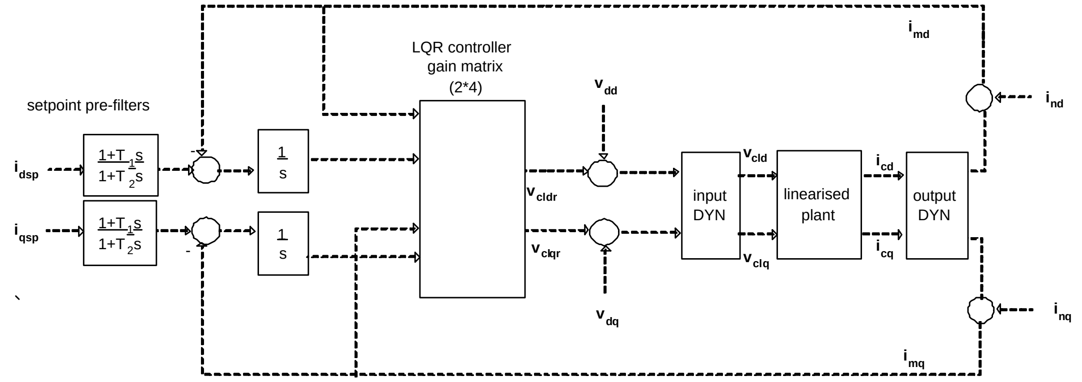

Figure 2: LQR Control structure for VSC

$$
\begin{aligned}
\dot{x} &= Ax + Bu \\
y_{linear} &= Cx \\
y_{nonlinear} &= h(y_{linear}, p)
\end{aligned}
\tag{6}
$$

where the inputs, linear outputs, nonlinear outputs and parameter vector are :

$$
\begin{aligned}
u &= [i_{spd}\ i_{spq}]^T \\
x &= [i_{cd}\ i_{cq}\ \frac{i_{cd}}{s}\ \frac{i_{cq}}{s}]^T \\
y_{linear} &= [i_{cd}\ i_{cq}\ v_{cld}\ v_{clq}]^T \\
y_{nonlinear} &= [P\ v_l]^T \\
p &= [v_s\ R_s\ L_s]
\end{aligned}
\tag{7}
$$

i.e. it is a linear system (A, B and C are the conventional state space matrices) with a static non-linearity appended to its output, the non-linearity being a function of the parameter vector p.

6.2 Control Design for VSC Attached to a Weak AC System

Calculation of the jacobian of h at a particular operating point allows small perturbations around the associated state x_0 to be analysed linearly. The resulting linearised model can then be used for design of a master control system for power and line voltage.

The controller structure studied is shown in Figure 3, and includes a ratio block for setting of i_{spd}. The open loop response from i_{spq} to v_l and P of the linearised model and an analytic non-linear model are shown on Figures 4 and 5 for operating points 1 to 3 (see Table 1) of the system considered; Table 1 also summarises model behaviours at other operating points. The open loop gain increases as power flow increases and SCR decreases, and at operating points 1-3 the linear model closely replicates the non-linear model and the PSCAD model. A linear controller designed for operating point 3 on the linear model is therefore anticipated to be stable for powers up to at least 0.25 pu at an SCR of 1.0.

The controller was designed for operating point 3 using the linear model. A pre-filter was included in the PID controller and the controller designed using an IMC SISO procedure [9].

o.p.	**SCR , power**	**description**
o.p. 1	SCR=4.0, power=0.25 pu	strong system,low power
o.p. 2	SCR=4.0, power=1.0 pu	strong system,high power
o.p. 3	SCR=1.0, power=0.25 pu	weak system,low power
o.p. 4	SCR=1.0, power=0.4 pu	highest PSCAD power with C.L stability at SCR=1.0 $\Delta P > 0.1$ pu
o.p. 5	SCR=1.0, power=0.6 pu	highest PSCAD power with C.L. stability at SCR=1.0 $\Delta P < 0.1$ pu
o.p. 6	SCR=1.0, power=0.79pu	highest theoretical power in steady state at SCR=1.0

Table 1: AC system operating points (o.p.). line voltage is 1.0 pu at all operating points

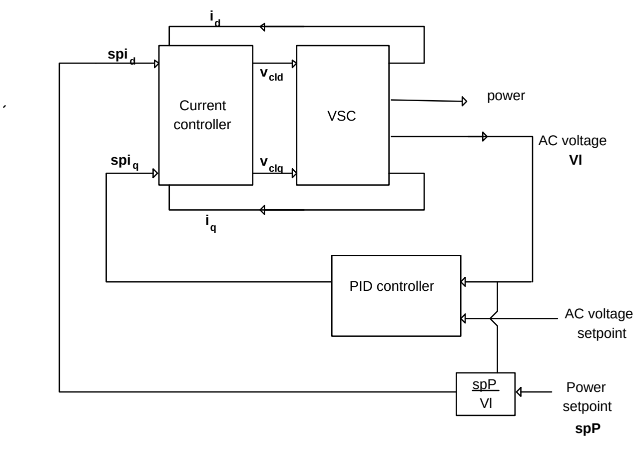

Figure 3: Power and Voltage Control

6.3 Validation of the AC Circuit Model

Satisfactory responses to power demand changes are achieved on the linearised model by setting of the IMC tuning parameter to values less than 2.0, but a value of 15.0 is required to avoid excessive oscillations with power step changes of greater than 0.1 pu on the PSCAD model.

The linear and PSCAD closed-loop power and voltage responses to power step changes at SCRs of 4.0 and 1.0 are compared on Figures 6 and 7. The linearised model behaviour closely matches that of the PSCAD model at SCR=4.0, but the PSCAD model exhibits light damping at SCR=1.0 not anticipated by the linear model.

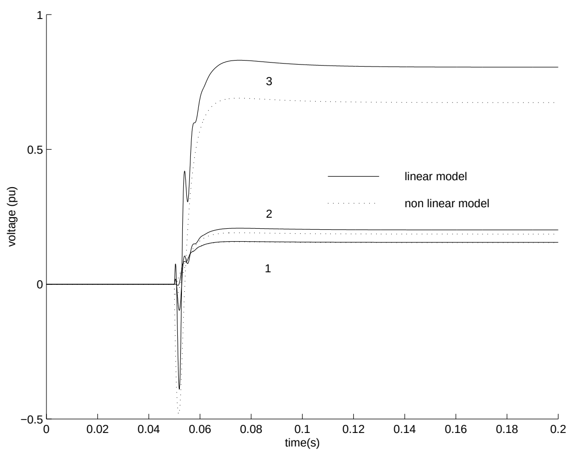

Figure 4:
Line voltage change responses to 0.5 pu Change in i_{spq} at 3 operating points, linear and nonlinear models

7 Conclusions

This paper demonstrates that the 2 state model of the VSC and the simple linearised model of the VSC connected to an AC system proposed here are adequate for control system design using linear methods for values of SCR greater than 4.0, but the controllers designed for values of SCR significantly less than 4.0 require detuning to avoid excessive oscillation. The key elements not captured in the extended model which cause the validation to deteriorate at low values of SCR are the AC filter and the phase tracking phase locked loops, the behaviour of which both become more significant at low values of SCR.

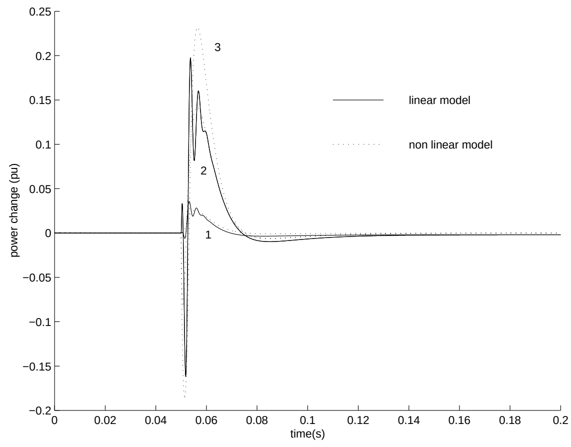

Figure 5:

Power responses to 0.5 pu Change in i_{spq} setpoint at 3 operating points, linear and non-linear models

8 Acknowledgements

This work has been jointly funded by EPSRC and ALSTOM T&D ltd.

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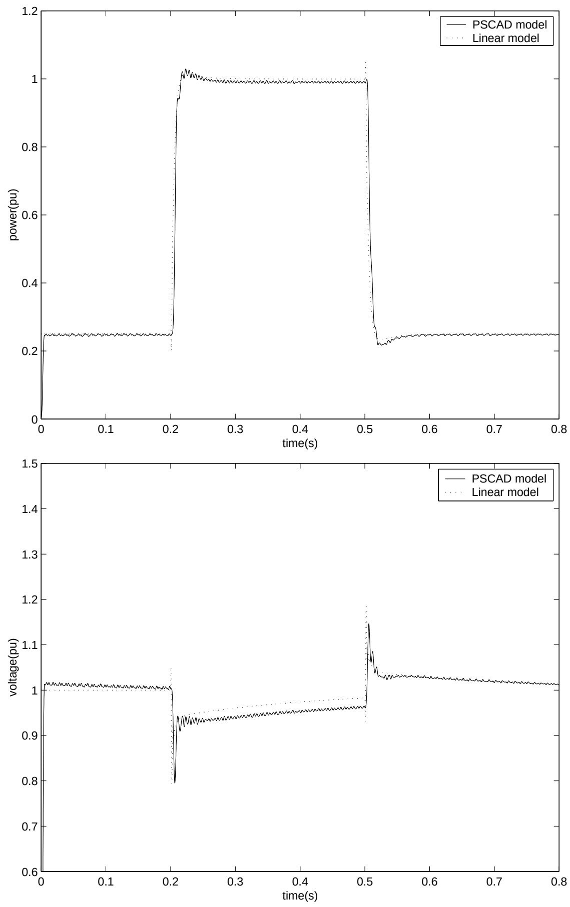

Figure 6:
Power and voltage responses to 1pu power setpoint step with LQR,operating point 1

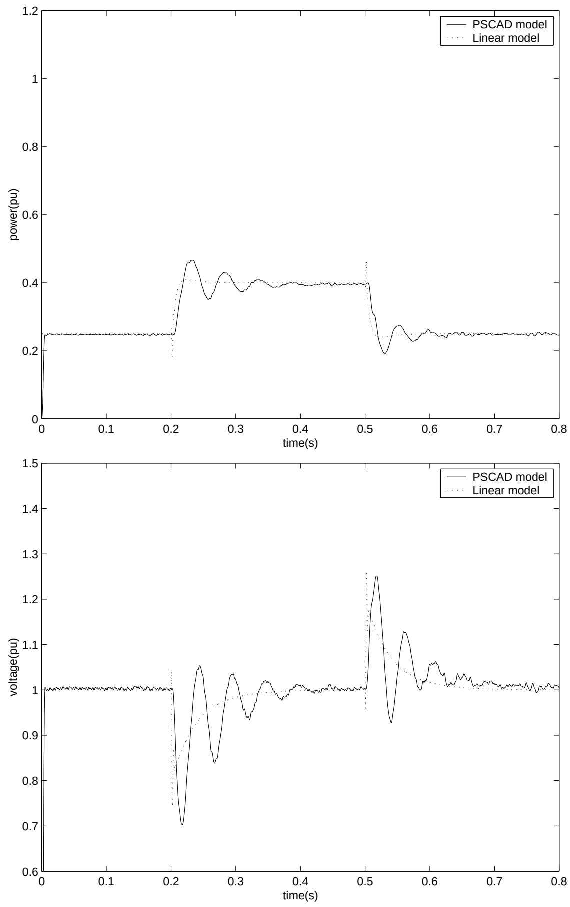

Figure 7:
Power and voltage responses to 1pu power setpoint step with LQR,operating point 3

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