DECENTRALISED CONTROL FOR DAMPING MULTI-MODAL OSCILLATIONS THROUGH CSC/VSC BASED HVDC TRANSMISSION TECHNOLOGIES

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Abstract

The damping of multi-modal oscillations through supplementary control of multiple HVDC systems is presented. The resulting controller produced is a fixed low-order decentralised controller, capable of providing adequate damping towards the low-frequency power oscillations. Linear analysis is substantiated with non-linear simulations in DIgSILENT PowerFactory with detailed representation of HVDC links.

1 Introduction

With major reinforcements worth approximately £4.7 billion by 2020 to accommodate 45 GWs of new generation, of which 34 GWs anticipated from wind to meet EU target of '15% energy from renewables' [1], the application of HVDC transmission technologies within the existing GB network as a means of enhancing the transfer capacity and improving the system dynamics is becoming more evident.

In recent years there has been vast interest into the application of decentralised control techniques to design damping control devices in power systems.

A number of approaches to decentralised control have been proposed [2-5]. However, the focus of most of them are on decentralised design of low-order PSS in a SISO or MIMO framework; or otherwise, on the robust control design techniques which evidently result in high order controllers and thus proving a practical limitation amongst the network operators.

Ramos et al. [4] used dynamic output feedback for decentralised design using LMIs considering multiple operating conditions. The controller order, however, is at least, as high as the open-loop plant. Messina et al. used a decentralised approach to co-ordinate multiple FACTs devices using classical control approach; however, it may lack robustness with varying operating conditions [5].

Modulation of the active power order of an HVDC link could be extremely effective for damping low-frequency power oscillations [6], thereby increasing the transfer capacity of an AC transmission system.

This paper examines the application of decentralised controllers through supplementary control of combined CSC/VSC HVDC systems for the damping of low-frequency electromechanical modes of oscillations which are inherent in large interconnected power systems.

Subspace-based, MIMO system identification is used to estimate and validate linearised state-space models through pseudo random binary sequence (PRBS) probing in DIgSILENT. The impact of both current source converter (CSC) and voltage source converter (VSC) based HVDC with only their primary control on the system stability is examined. VSC stations offer damping services at both ends of the line which could raise the stability limit of the remaining AC routes through modulation of either the active or reactive powers, or both, at each converter station. Hence, offering more flexibility than CSC systems where only the active power can be modulated. There are tremendous potential for VSC-HVDC systems to contribute towards improvement in AC system dynamics. Here, secondary control among the available control variables in both CSC-HVDC and VSC-HVDC is demonstrated. The objective here is to establish by how much transmission system capacity might be improved by raising the AC stability limits through a series of DC upgrades with secondary control action.

The contributions of this paper are as follows:

- Development of detailed HVDC models in DIgSILENT PowerFactory
- MIMO system identification and validation using sub-space state-space system identification (N4SID)
- The design of a decentralised controller to damp multiple swing modes through CSC/VSC HVDC devices
- Validate the findings through linear and non-linear simulations in DIgSILENT PowerFactory

2 Test Cases in DIgSILENT

2.1 Test System

A 14-machine, 59-bus study system, shown in Fig.1, was considered for the case study. This system has been recently adopted as an IEEE benchmark for stability studies [7].

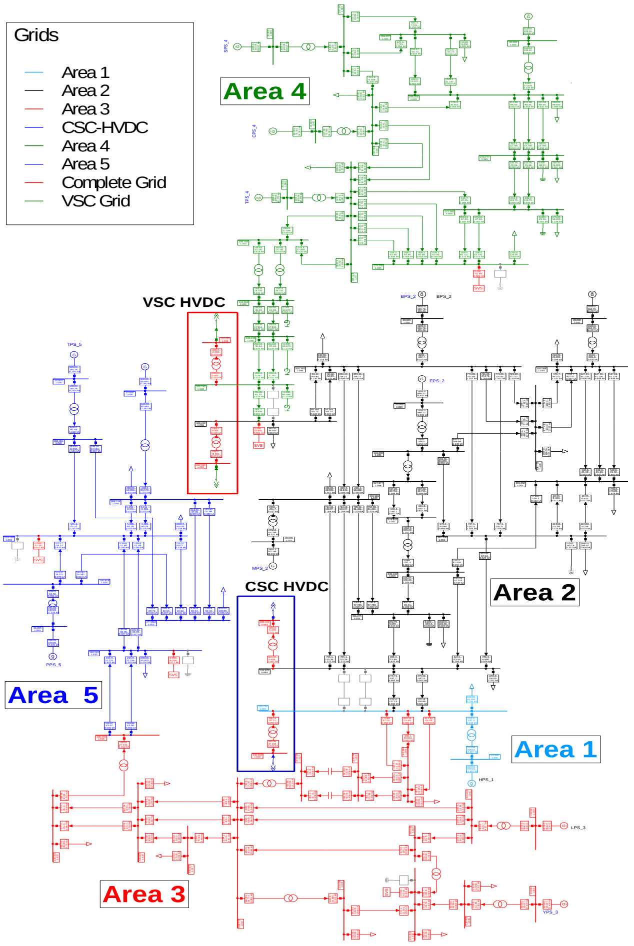

Figure 1 Simplified 14-machine equivalent of Australian system modelled in DIgSILENT

The detailed description of the study system including network data and dynamics data for the generators, excitation systems, PSSs and SVCs can be obtained from [7]. The network constitutes of 5 areas in which areas 1 and 2 are more closely coupled electrically. Therefore, in essence the power system is made of 4 main regions and has 3 inter-area modes, as well as 10 local-area modes. The machines are equipped with either IEEE type AC1A, AC4A or ST5B excitation system models. All generators are supplied with speed-input power system stabilizers of second and fourth order transfer functions. Five Static VAr Compensators (SVCs), set in voltage control mode, are installed at nominated bus terminals (1 in each area), to improve the voltage profile of the system. The loads are all assumed to be of Constant Impedance (CI) type for all operating conditions.

2.2 Problem Formulation

The power system shown in Fig.1 was modelled and benchmarked against standard results [7] in DIgSILENT PowerFactory. To investigate power oscillation damping (POD) control through HVDC, 6 of the 14 PSSs were placed out of service to create a more oscillatory behaviour (see Table 1 for relative damping and frequency of inter-area modes). A point-to-point VSC- HVDC link was added in parallel to the AC corridors between area 2 and area 4 and a CSC- HVDC link was added in parallel to the AC corridors in area 1 and area 2 (see Figure 2).

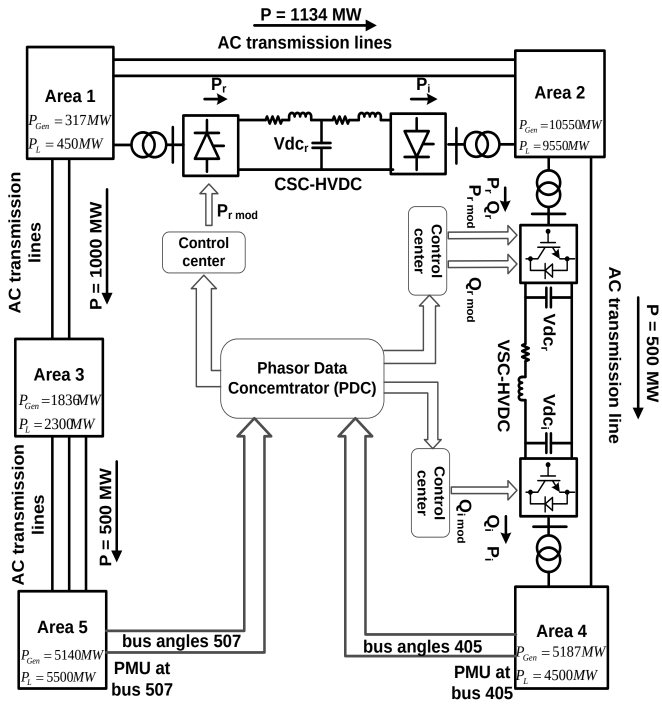

Figure 2 14-machine, 5-area test system with CSC-HVDC and VSC-HVDC link. Secondary control loops with PMU signals are shown

Both CSC and VSC based HVDC systems are modelled in detail in DIgSILENT Power Factory. The primary controls for CSC-HVDC is based on the CIGRE benchmark model [8] with rating of +/- 500kV, 1000MW link. The VSC link has rating of +/- 150kV, 350MW.

The DC links accommodate 50% of the total inter-area flows (originally accounted by the AC lines but now placed out of service - see grey transmission lines in Fig.1). Out of several scenarios considered the heavy loading scenario is presented here. In steady-state operation the active power order for CSC-HVDC was set to 50% of 1134MW and VSC-HVDC accommodating 50% of 500MW. The reactive power order was set to maintain close to unity power factor at the AC bus terminals.

The problem is then formulated as the ability of the converter stations to provide services that enable optimised power flow and stabilising services (through control centres) for extending the stability limit of the AC network.

3 Design Approach

3.1 Linear Model Estimation and Validation

Since it is not possible to directly obtain the linearised system models from DIgSILENT then system identification technique was used to estimate the linear model from the simulated outputs in response to appropriate probing signals at the inputs. Here, the linear model has 3 control inputs - Pr, Qr and Qi for the VSC HVDC and 1 control inputs – Pr for the CSC HVDC and 16 possible phase angle measurements available from the PMUs. Identification of such MIMO systems is quite challenging and gets further complicated with increase in number of output signals [9]

The amplitude of the PRBS was chosen to be high enough to sufficiently excite the critical modes without pushing the responses into nonlinear zone. Persistent excitation of at least the model order of interest was provided. Moreover, the probing sequence for different inputs was ensured to be uncorrelated [10]. Typical PRBS injection signals used for probing the test system is shown in Fig. 3.

The process for model identification and validation is illustrated in Fig.4. Using the input probing signal $\{u_i(0), u_i(1), \ldots u_i(N), i = 1, 2, \ldots 4\}$ and output responses $\{y_i(0), y_i(1), \ldots y_i(N),\ i = 1, 2, \ldots 16\}$ the matrices A_d, B_d, C_d and D_d were calculated such that the simulated data resembled the responses from the estimated linear model. Numerical algorithm for subspace state space system identification (N4SID) [11] was used to estimate the above matrices. A model order of 35 was found to be appropriate. To validate the model an input pulse signal was applied to the identified and full model (see Fig.4).

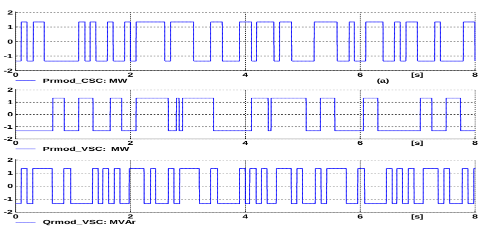

Figure 3 Typical PRBS injection used for system identification

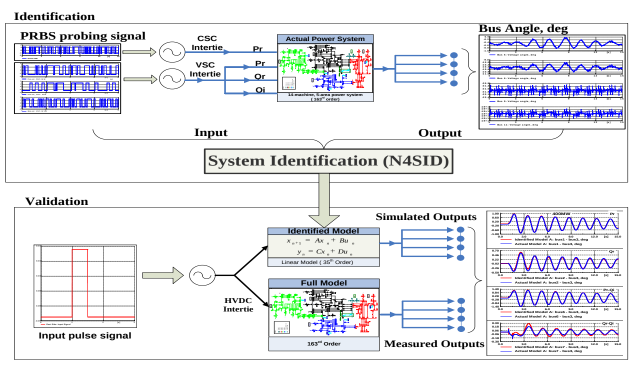

Figure 4 Model identification and validation process

3.2 Signal Selection

Product of modal controllability and observability gives the Residue $Res_{i-kj} = Co_{ik} \times Ob_{ij}$ which indicates the extent to which mode i can be observed and controlled through input k and output j. The elements of an eigenvector are complex numbers, in general, and as such modal controllability Co_{ij}, modal observability Ob_{ik} and residue Res_{i-kj} are all complex numbers with a magnitude and a phase angle component.

Once the residues corresponding to all possible input-output combinations are calculated and sorted in descending order of magnitude, the appropriate ones are chosen from the top (with highest residues) to ensure minimum control effort. Bus angles 405 and 507 (from area 4 and 5 respectively) yielded the highest residues and are subsequently chosen as the feedback signals for the damping controller.

3.3 Controller Design

In this work a decentralised control framework is used at the rectifier and inverter end control centres of the HVDC transmission systems (see Fig. 2). There are 4 possible control (modulation) inputs Prmod, Qrmod, Qimod (for VSC-HVDC) and Prmod (for CSC-HVDC), and 16 pre-selected outputs - the phase angles measured by the PMUs installed at 16 buses. Residues were calculated for all possible input-output combinations. For the case study presented, it was found from modal residues that modulating the CSC-HVDC active power and reactive power on rectifier side of VSC-HVDC would effectively meet the design objective of 10.0 s settling. Further control centres can obviously be used to possibly provide improved results. The conceptual representation of a decentralised control system for MIMO systems is shown in Fig. 5.

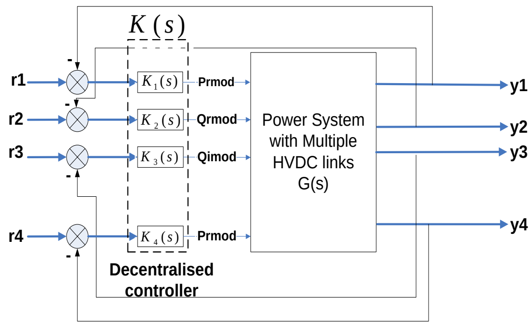

Figure 5 Conceptual representation of a decentralised control system for damping control

A control system is referred to as decentralised if the off-diagonal elements of the controller transfer function matrices are zero, as shown in the equation $K(s)$ below.

$$K(s) = \begin{bmatrix} K_1(s) & 0 & . & 0 \\ 0 & K_2(s) & . & 0 \\ . & . & . & 0 \\ 0 & 0 & 0 & K_m(s) \end{bmatrix}$$

It follows that each control centre $K_i(s)$ can be designed for individual HVDC converter station without any loss of performance or interacting with other control loops [12]. It is important to structurally decompose the decentralised control system into individual SISO loops to reduce the problems of interaction [5].The system consists of a set of SISO loops as shown in Fig.6.

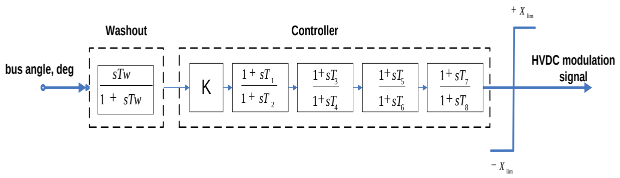

Figure 6 Control centres composed of individual decentralised control, $K_i(s)$

The use of decentralised structure can result in performance degradation compared to a full feedback system. However, it leads to reduction in the number of tuning parameters, simplified hardware and is vastly used by industry compared to a centralised approach.

3.4 Controller Synthesis

The decentralised damping controller is required to ensure a settling time of 10.0 s for all operating conditions considered during the design stage whilst ensuring optimum control effort is achieved. An objective function is minimised such that that the poles of the closed loop system are properly placed under each scenario. The objective function is as follows:

$$F = \sum_{j=1}^{3} \alpha_j \times f_j$$

Subject to the following constraints,

$$f_1 = \sum_{p=1}^{n} \sum_{q=1}^{k} (\sigma_{\text{ref}} - \sigma_{pq})^2 \qquad f_2 = \sum_{p=1}^{n} \sum_{q=1}^{k} (\zeta_{\text{ref}} - \zeta_{pq})^2$$

Any evolutionary technique can be used to solve this multi-objective constrained optimisation problem (i.e. genetic algorithm, particle swarm optimisation). The resulting controller is a 2-input, 2-outputs, with each channel of 4th order (see Fig.6). The controller was obtained using a PSO technique. The interested reader is referred to [13].

4 Simulation Results

4.1 Linear Analysis

The location of the open-loop (blue) and closed-loop (black) poles (dominant modes of interest) are shown in Fig.7 for the nominal operating condition. A direct left shift for the three critical poles beyond the respective reference damping ratio lines can be observed with minimal frequency variation (shown by the arrow).

The robustness of the designed controller is evaluated in terms of damping ratio (ζ), frequency of oscillation (ω) and the settling time (T_s) for each individual modal oscillations across a range of operating conditions. Due to limited space the results presented here are for the nominal operating point.

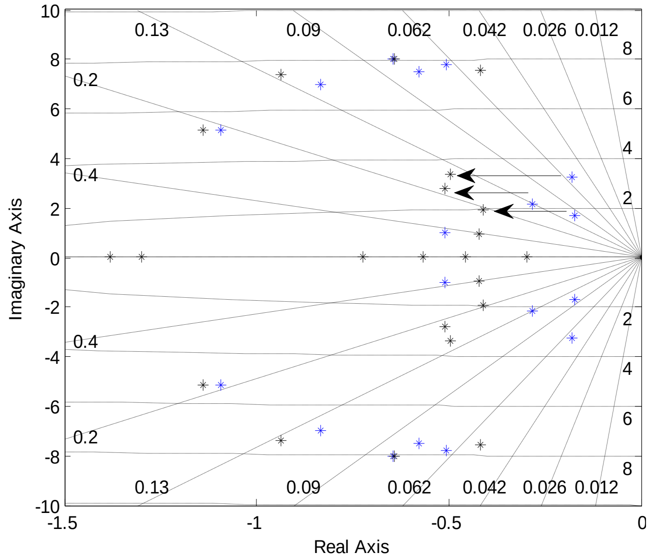

Figure 7 Location of open-loop and closed-loop poles (not including the higher frequency and fast settling modes) under nominal operating condition

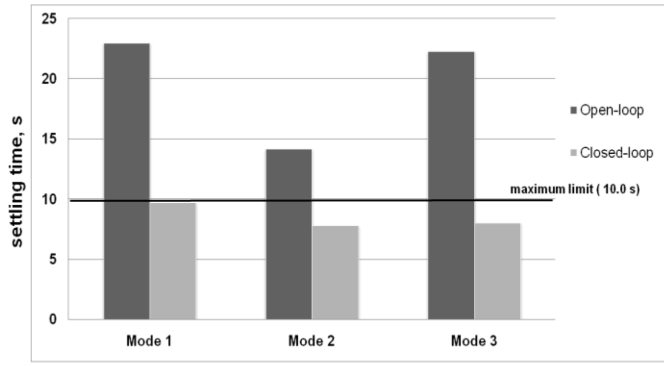

Figure 8 Open-loop and closed-loop settling times (in sec) for the three modal oscillations under the nominal operating condition.

The closed-loop settling times for the critical inter-area modes, shown in Fig.8, are within the target settling time of 10.0 s. This indicates that the original design specification (specified by the horizontal solid line) is achieved.

The impact of both VSC and CSC based HVDC systems within the AC system on the relative damping ratio (ζ) and modal frequency (f) with only their primary control is shown in Table 1.

Referring to Table 1, in closed-loop, c), it can be seen that the damping ratios are significantly improved from those in b) to achieve the minimum settling time (see bold-faced). The range of frequency variation is not too significant; 0.03 Hz (0.27 – 0.30Hz), 0.1Hz (0.35-0.45Hz) and 0.01Hz (0.52-0.53Hz) for modes 1, 2 and 3, respectively. A constraint on the frequency can be considered in the design stage to minimise the variation but the impact is not considerable.

Mode no.	a) AC system only		b) with multiple HVDC		c) Multiple HVDC + POD	
	ζ, %	***f*, Hz**	**ζ, %**	***f*, Hz**	**ζ, %**	***f*, Hz**
1	10.1	0.29	**10.2**	0.27	**20.7**	0.30
2	11.1	0.35	**12.9**	0.35	**18.0**	0.45
3	6.5	0.55	**5.5**	0.52	**14.6**	0.53

Table 1 Relative damping ratio, ζ, and modal frequency, f, of multiple HVDC with primary controls (b) and with POD control (c) against AC system only (a) for the nominal operating condition.

The performance in presence of nonlinearities is presented in the next section through time domain simulations.

4.2 Nonlinear Simulation

Nonlinear simulations are conducted in DIgSILENT PowerFactory to demonstrate the performance of the designed controller. A severe three-phase solid fault at a critical bus (Inverter-side of CSC) for 5 cycles (100ms) followed by outage of one of the adjacent lines between area 1 and area 2 is simulated.

The top two subplots (a, b) show the angular separation between G503, G301 with the slack generator G101; the power flow in the AC corridor between areas 2- 4 is exhibited in (c) and the HVDC modulation signals required to damp out the oscillation's is shown in (d). The CSC-HVDC bus voltage ends are shown in (e, f) and finally the VSC-HVDC Inverter d-axis and q-axis currents (I_{di} and I_{qi}) are plotted in (g and h) respectively.

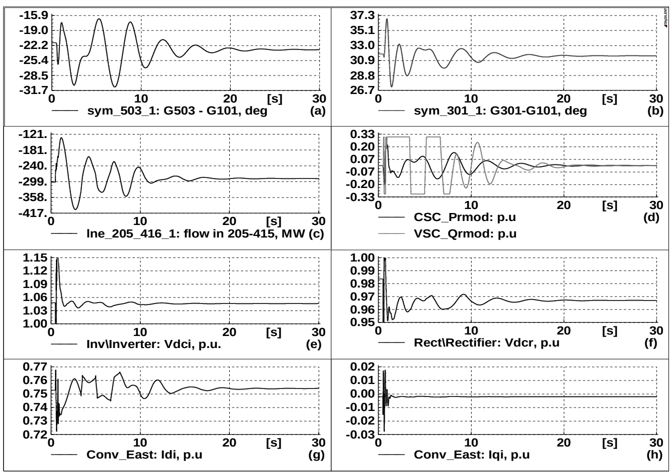

Figure 9 Dynamic behaviour of the system following a fault at bus 102 for 5 cycles and subsequent outage of line 102_207

Figure 9 (a, b, c) show that oscillations settle slightly beyond 10.0 s. This is due to the severity of the fault which has violated the limits of the VSC-HVDC, as is evident from (d). It is also clear from (d) that a considerably higher control effort is demanded from reactive power VSC modulation signal Qrmod as compared to the modulation signal required from the CSC Pr mod. During the fault, the dc bus voltages at both HVDC ends drop sharply due to reduction of ac side power transfer. This is followed by oscillations in Vdcr due to the dc link dynamics while the Vdci is regulated to a constant value, see subplots (e, f). Because of the magnitude of the fault close to inverter bus, Idi is seen to violate its respective limits, see subplot (g).

5 Summary

The damping of multi-modal oscillations through supplementary control of multiple HVDC systems is presented. It was found that active power modulation through CSC and reactive power modulation through VSC provided adequate damping through an 8^{th} order (2input- 2output) decentralised controller.

Acknowledgements

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