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On small signal stability of an AC/DC power system with a hybrid MTDC network

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ABSTRACT

Multi-terminal HVDC (MTDC) networks are being contemplated for large scale integration of renewable energy sources, as well as for the interconnection of asynchronous AC systems. A hybrid MTDC network that combines line commutated converters (LCCs) and voltage source converters (VSCs) can combine the benefits of both technologies. This paper presents a mathematical model of an AC/DC power system with an embedded hybrid MTDC network interconnection. Small signal stability analysis of the power system is conducted based on the linearization of the model. The impact of VSC controller gains on the dominant modes in the system is investigated. The contributions of the converters and generators to different modes of the system are investigated based on the participation matrix analysis. Auxiliary controllers are applied at the converters for the purpose of damping power oscillations in case of disturbances. The results of small signal stability analysis are validated by time-domain simulations in MATLAB.

1. Introduction

Multi-terminal HVDC (MTDC) networks have been considered as a prospective solution for the interconnection of asynchronous power systems, as well as for large scale integration of renewable energy sources. Voltage source converters (VSCs) are expected to dominate MTDC networks, as VSCs are capable of achieving multiple benefits to the connected AC system. The main advantages of VSCs as compared to line commutated converters (LCCs) are: the independent control of active and reactive power, and the ability to connect to weak or passive AC grids. Despite their shortcomings when operated with weak AC grids [1,26], LCCs have the advantages of low cost and low power losses as compared to VSCs. Therefore, a hybrid MTDC system can combine the benefits of both LCC and VSC converters. The benefits namely include reduced total system cost and power losses thanks to the LCCs, as well as the flexibility to connect to weak and passive grids due to the deployment of VSCs.

A hybrid point-to-point HVDC system combining both LCCs and VSCs was first proposed in literature in 1994 in [1]. Typical applications included power transmission to islands as suggested in [2,3]. Hybrid MTDC was first contemplated in the literature in 1999 in [4]. The authors in [5] have dealt with a hybrid multi-infeed (MI) HVDC system in which a passive AC network was fed by both LCC and VSC converters. However, each of the converters at the receiving end was supplied by an identical converter at the sending end. The authors in [6,7] investigated the control and performance of a hybrid MTDC system through simulation studies in EMTDC/PSCAD. The control and performance of hybrid MTDC networks used for the integration of wind power was covered in [8–11]. The DC voltage control strategies used in hybrid MTDC networks are generally the same as those used in VSC-MTDC networks, with the possibility to control DC voltage at the VSC or at the LCC [2,12].

The small signal stability analysis (SSSA) of LCC-HVDC systems was covered extensively in the literature. The approach followed in [19,20] was to combine the linearized small-signal converter models with the generator models. However, the validation of small-signal models by time-domain simulations was conducted in simulation platforms that use different nonlinear models for representing the AC/DC power system. Compared to LCC-HVDC, fewer studies dealt with SSSA of VSC-MTDC. The SSSA of VSC-MTDC in [21] was based on the linearization of the model used in time-domain simulations. The approach followed in [21] provided a unified platform for both time-domain simulation and SSSA of an AC/DC power system with an embedded VSC-MTDC, thanks to the SSSA being based on the linearization of the same model used in time-domain simulation. The authors in [16] presented an approach for load flow of AC/DC power systems incorporating VSC-MTDC networks. The approach is based on the sequential method for AC/DC load

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flow. The stability of VSC-MTDC networks was also studied in [17] based on both average model in MATLAB and switched model in EMTDC/PSCAD.

Although multiple investigations on the control and performance of hybrid MTDC networks are found in the literature, however there has been little focus on the study of SSSA of the AC/DC power system incorporating a hybrid MTDC network. The authors in [22] presented SSSA of a hybrid MTDC system. The formulation of small-signal model was based on the linear model obtained through system identification. However, the paper did not investigate the effect of LCC and VSC controller gains on small-signal stability. Moreover, the model obtained through system identification approach is dependent on the specific configuration of the power system and the time-domain simulation program. Therefore the model obtained through system identification cannot be easily extended to other DC network or power system configurations. This paper presents a mathematical model of an AC/DC power system incorporating a hybrid MTDC network. The model is then used to perform a SSSA of the combined AC/DC system. The model of hybrid MTDC system is formulated by combining the individual models of LCC, VSC, and DC line. The LCC is represented by the response model [13], which considers the firing angle and DC current dynamics. The response model is suitable for stability studies [13,19]. On the other hand, the VSC is represented by the injection model [14,15], which considers the VSC as an AC source with controllable magnitude and phase angle. The DC line is represented by its series resistance and inductance. The model of hybrid MTDC components was presented in a modular approach that is readily extendable to various configurations of DC networks and AC grids. The combined AC/DC power system model was represented by differential algebraic equations (DAE). The differential equations represent the state equations, while the algebraic equations represent the power mismatch equations of the AC/DC load flow. The AC/DC load flow is performed based on the unified method [27]. The SSSA is conducted based on the linearization of the AC/DC power system model. The effect of VSC controller gains on the electromechanical modes of the system is investigated and discussed. The results from SSSA are validated by time-domain simulation in MATLAB. Power oscillation damping (POD) controllers are designed based on the results obtained from SSSA. The main contribution of this paper is to present a unified model that serves as a platform for both time-domain simulation and SSSA of an AC/DC power system with a hybrid MTDC network. The paper also highlights the importance of SSSA as a benchmark tool for the analysis of control interactions between converter and generator controls.

The paper is organized as follows: Section 2 provides the models of MTDC network components and their controllers, Section 3 provides a general framework for the establishment of the DAE model for an AC/DC power system with a hybrid MTDC network. Section 4 provides the DAE model of a test AC/DC power system, Section 5 presents the methodology followed for SSSA of the combined AC/DC system. Section 6 studies the effect of controller gains, as well as POD controllers, on the small-signal stability of the system. Finally Section 7 gives the conclusions of the paper.

2. Mathematical model of hybrid MTDC network components

2.1. DC line model

The DC line is represented by its π equivalent model, as shown in Fig. 1. Based on the figure, the state equation of DC line current can be given as follows:

$$\frac{dI_{ij}}{dt} = \frac{1}{L_{line}}(V_i - I_{ij}R_{line} - V_j) \tag{1}$$

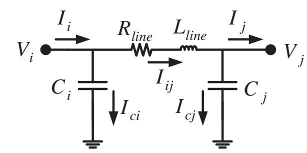

Fig. 1. DC line model.

where L_{line} and R_{line} are the line inductance and line resistance, respectively. V_i and V_j are the DC voltage at the two ends of the line. The state equations for DC voltages at the line ends are given as follows:

$$\frac{dV_i}{dt} = \frac{1}{C_i}(I_i - I_{ij}) \tag{2}$$

$$\frac{dV_j}{dt} = \frac{1}{C_j}(I_{ij} - I_j) \tag{3}$$

where $C_i = C_j = \frac{C_{line}}{2}$, and C_{line} is the line capacitance.

2.2. LCC model

The LCC was represented by the response model. The response model is suitable for stability studies, as it represents the basic quantities involved in the operation of the LCC, such as the DC current (I_{dc}) and the firing angle (α). The LCC representation is shown in Fig. 2.

The state equation for the DC current of the LCC is given as follows:

$$\frac{dI_{dc}}{dt} = \frac{1}{L_{dc}}(V_{LCC} - V_i) \tag{4}$$

where V_{LCC} is the LCC's output DC voltage and V_i is the DC network voltage at the LCC terminal. V_{LCC} is given as follows:

$$V_{LCC} = V_{dc10}\cos(\alpha) - c_{LCC}I_{dc} \tag{5}$$

where V_{dc10} is the no-load output voltage of the LCC, and c_{LCC} is the DC current constant of the LCC. The constants V_{dc10} and c_{LCC} are given by:

$$V_{dc10} = \frac{3N_b\sqrt{2}}{\pi}U_{bus} \tag{6}$$

$$c_{LCC} = \frac{3x_t}{\pi} \tag{7}$$

where N_b is the number of bridges in the LCC, U_{bus} is the magnitude of converter bus voltage, and x_t is the reactance of converter transformer.

2.3. VSC model

The VSC model is shown in Fig. 3, where V_i is the DC voltage at the VSC terminal, C_{dc} is the capacitor installed across the DC side of VSC, x_T is the reactance of converter transformer, $\bar{U}$ is AC voltage of the converter bus, and $\bar{E}_c$ is the controllable voltage of the VSC. The AC voltage at the converter bus is given by $\bar{U} = Ue^{j\theta}$. Based on

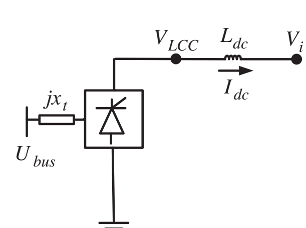

Fig. 2. LCC converter.