Load margin for short-term voltage stability of an interconnected AC/MTDC system

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Abstract: The so-called short-term voltage stability is typical of nonlinear problems arising in dynamic performance of electric power systems. This paper reports a simulation result on load margin for short-term voltage stability of the IEEE 9-bus system connected to a multi-terminal DC system based on voltage-source converter (VSC). The simulation shows that the introduction of AC voltage control in VSC increases the load margin under a step change in load on the AC system, thereby showing a clear benefit of the AC voltage control for enhancing the short-term voltage stability without harnessing the AC system.

Key Words: multi-terminal DC system, interconnected power system, short-term voltage stability, AC voltage control

1. Introduction

The Multi-Terminal DC (MTDC) system based on Voltage-Source Converter (VSC) has clear advantages for reliability enhancement of existing AC systems by rerouting the power flow in failure and increasing the reserve capacity of power generation: see, e.g., [1]. In this, the VSC-based MTDC system is expected to cooperate connecting AC systems in terms of enhancement of small-signal stability, frequency stability, and voltage stability [2].

This paper addresses the so-called short-term voltage stability of a multi-machine AC system connected to a VSC-based MTDC system. In [3], the short-term voltage stability involves dynamics of fast acting load components and HVDC converters, while the phenomenon of interest develops in the time scale of several seconds and by significant influence of nonlinearity in power systems. Analysis of the stability is of basic importance for understanding the dynamic performance of interconnected
Fig. 1. VSC-based MTDC system with all-to-all coupling which we study in this paper. The three VSCs (VSC1, VSC2, and VSC3) are connected to the three buses in the IEEE 9-bus system [10] which are denoted above with the same circled numbers 4, 7, and 9 in Fig. 2.18 therein.

AC/MTDC systems. In literature, the frequency stability of AC systems with and without frequency droop control of VSC was estimated in [1, 4]. In these, the detailed dynamics of frequency and voltage were considered under a step increase in load on the AC systems. However, to the best of the authors’ survey, no research is archived that explicitly considers voltage dynamics and instabilities in short-term regime. The explicit consideration is motivated by the fact that the short-term stability becomes serious concern in low inertia systems, see, e.g., [5].

The purpose of this paper is to report a simulation result on the short-term voltage stability of a rudimental interconnected AC/MTDC system with emphasis on AC voltage control [2, 6] of VSC. The reason why we emphasize the AC voltage control is that it is expected to improve the so-called weak AC grids [2]. Due to high values of transmission impedance in such weak grids, the magnitude of load voltage can significantly change and deteriorate the degree of voltage stability. This requires the compensation (including generation and consumption in the grids) of reactive power in order to keep the load voltage within an acceptable range. The compensation is effectively enabled by the introduction of AC voltage control in VSC. This is regarded as an ancillary service provided by VSC that is less costly in comparison with the introduction of new apparatuses for reactive-power compensation (such as shunt capacitors and power electronics-interfaced circuits), implying its potential in real applications. For this, we calculate the upper limit of step increase in a load when the AC/MTDC system can critically maintain an acceptable condition of voltage amplitudes in the AC system. The upper limit of step increase is defined as the load margin for short-term voltage stability. The calculation is conducted with large-signal simulations of the AC/MTDC system using the modular modeling framework previously reported in [7]. The contribution of this paper is to quantitatively show a clear benefit of the AC voltage control of VSC for enhancing the load margin for short-term voltage stability of the AC/MTDC system. It should be noted that the calculation of load margin poses the study of nonlinear dynamics in which we evaluate a set of trajectories, parametrized by the amount of step increase, in a model of nonlinear Differential-Algebraic Equation (DAE) by checking whether it tends to converge to an asymptotically stable equilibrium point. As shown in our previous paper [8], the convergence is governed by the global structure of solutions of the DAE referred to as stability region of the stable equilibrium point. In this sense, we focus in this paper on the nonlinear problem motivated by the clear engineering application.
2. Model of interconnected AC/MTDC system

This section outlines the model of interconnected AC/MTDC system simulated in this paper. A test model of interconnected AC/HVDC systems was developed within the works presented in [9] using the IEEE 9-bus system [10] and a VSC-based HVDC system. An extension of it to MTDC system is analyzed in this paper by taking the MTDC system of [7], which is shown in Fig. 1. The three VSCs, VSC1, VSC2, and VSC3, are connected to the three buses in the IEEE 9-bus system shown with the same circled numbers $4$, $7$, and $9$ in Fig. 2.18 of [10]. The MTDC system has the all-to-all coupling topology and thus affects voltages in the entire AC system, whose dynamic situation is our concern in this paper.

Next, the representation of dynamics in the AC and MTDC systems is briefly described. The three synchronous generators in the IEEE 9-bus system are represented with the one $d$-axis model with Automatic Voltage Regulator (AVR Type I) and Turbine-Governor (TG Type II) [11]. No slack bus in the AC system is assumed in dynamic simulations. The AC transmission lines are symmetrical and represented with the $\pi$-type equivalent model. All electricity consumption in the AC system is represented with constant power loads. For the MTDC system in Fig. 1, all the DC transmission lines are of bipolar type and modeled with the $\pi$-type equivalent model [2]. The model is represented as follows:

$$
\begin{align*}
L_{dcij} \frac{di_{dcij}}{dt} &= -R_{dcij}i_{dcij} + v_{dc1} - v_{dcj} \\
C_{dc} \frac{dv_{dc1}}{dt} &= i_{dc1} - \sum_{j \neq i}^{3} i_{dcij}
\end{align*}
$$

(1)

where $L_{dcij}$ and $R_{dcij}$ are the reactance and resistance between $i$-th and $j$-th buses, and $C_{dc}$ is the capacitance of $i$-th node. The variable $i_{dcij}$ is the current flowing from $i$-th to $j$-th bus, $v_{dc1}$ is the voltage of $i$-th node, and $i_{dc1}$ is the current flowing to the MTDC system (from an AC one) through VSC at $i$-th bus (see Fig. 1). The capacitance is given by $C_{dc1} = C_{sdc1} + \sum_{j \neq i}^{3} C_{dcij}/2$, where $C_{sdc1}$ is the smoothing capacitance of VSC, and $C_{dc1}$ is the line capacitance between $i$-th and $j$-th buses. The current $i_{dc1}$ in (1) is an important variable that represents the dynamic interaction from the AC to the MTDC system. In this paper, because no loss in VSC is assumed as in [7], $i_{dc1}$ in (1) is represented as follows:

$$
i_{dc1} = \frac{p_{dc}}{v_{dc}} = i_{cv,d}v_{cv,d} + i_{cv,q}v_{cv,q}$$

(2)

where $p_{dc}$ is the active power converting via VSC, $v_{cv,d}, v_{cv,q}$ are the AC-side voltages of VSC, and $i_{cv,d}, i_{cv,q}$ are the currents flowing to the AC system (from the MTDC one) through VSC. See [8] for the details of the DC modeling.

Finally, the control models of the three VSCs in Fig. 1 are explained. A master-slave control (see, e.g., [12]) is applied to the control scheme of the three VSCs. In this scheme, one master-VSC and two slave-VSCs are assigned in the MTDC system. The master-VSC mainly regulates the DC voltage, and the slave-VSCs do the active power. In addition to this, the three VSCs can regulate AC voltage or reactive power, which is our main concern in this paper. The block diagrams of VSC control used here are based on [6, 13] and shown in Fig. 2. Figure 2b is derived by replacing the active power in [6] with the DC voltage. Each controller changes the reference value of the currents $i_{cv,d}, i_{cv,q}$ by the PI (Proportional-Integral) rule. In Fig. 2a, the droop controller is introduced for the DC voltage. The master-VSC uses the control diagrams of Figs. 2b and 2c. The slave-VSCs use Figs. 2a and 2c as the control diagrams.

By combing the modular models of AC and MTDC systems into one system, it is possible to derive a nonlinear DAE model that represents the short-term voltage dynamics of the interconnected AC/MTDC system. Although simplification adopted for the synchronous generator, see [8] for the DAE model.
Block diagrams for control of voltage-source converters (VSCs). The superscript $^\ast$ represents a reference value, $d$ (or $q$) does the value transformed into the $d$ (or $q$) reference frame. $p_m$ and $v_{om}$ are the measured active power and AC voltage of the AC side of the filter in VSC. $v_{dcm}$ is the measured DC voltage.

3. Investigation of load margin

First, the setting for numerical simulations is summarized. The values of variables and parameters are normalized with the PU (Per-Unit) system. The base quantities of the PU system were 300 MVA and 230 kV for the AC system, and 300 MW and 200 kV for the MTDC system. The nominal frequency of the AC system was set at 60 Hz. Basically, the parameters of the AC system are from [10], except for the models of AVR and TG which are taken from [14]. The parameters of the MTDC system are based on [7]. The setting of parameters of the VSC controllers is basically from [6] and changed according to our simulation purpose.

In this paper, in order to evaluate how the short-term voltage stability is affected by the presence of AC voltage controllers, we do not change the values of parameters of the VSC controllers (except for the presence of AC voltage controllers). A common initial condition of the state variables of the nonlinear DAE model is thus used for all simulations with and without the AC voltage control, where the effect of AC voltage control can be solely investigated.

Next, the analysis method and disturbance adopted in this paper are explained. All numerical integrations of the model were performed in MATLAB with the implicit trapezoidal method [11]. The fixed time-step of the implicit trapezoidal method was 100 $\mu$s. We supposed that at time $t=0$ s the AC/MTDC system was at a normal operating condition (that is, a stable equilibrium point of the DAE model), and at $t=0.1$ s a step increase in load at one of the three buses labeled as $5\,^\circ$, $6\,^\circ$, and $8\,^\circ$ in Fig. 2.18 of [10] happened. Note that no concurrent increase of load happens in this study: for example, if the step increase in active power at bus $5\,^\circ$ happens, then the loading condition of reactive power at bus $5\,^\circ$ and of active/reactive power at buses $6\,^\circ$ and $8\,^\circ$ are at normal conditions. In this paper, we determined the upper limit of load increase when the AC/MTDC system can critically maintain an acceptable condition of voltage amplitudes in the AC system. Precisely, we checked after a load increase whether the trajectory of the DAE model converged to a new stable equilibrium point with the acceptable values of voltages. As defined in Section 1, this upper limit of load increase is referred to as the load margin for short-term voltage stability. Multiple simulations during 10 s were conducted for both the cases with and without the AC voltage control.

Finally, we present the numerical results and implications regarding the main result. Figure 3 shows an example of the evolvement over time of voltage amplitude at bus $5\,^\circ$ in the AC system of Fig. 1. They are initiated by the step increase in active power at bus $5\,^\circ$ (see again Fig. 2.18 of [10]). The blue line represents the evolvement with the AC voltage control, and the orange line without the AC voltage control. The difference of Figs. 3a and 3b is the amount of load increase (160 MW for (a) and 80 MW for (b)). For the large increase in Fig. 3a, the orange line, namely, the voltage dynamics

__MATLAB code d_009_LG.mdl included in Power System Analysis Toolbox (PSAT) ver 2.1.11__
Fig. 3. Time evolutions of voltage amplitude at bus 4 against step increase in active power at bus 5 (in Fig. 2.18 of [10]). The oscillation and decrease of voltage amplitudes in order of 1 s, which are kinds of short-term phenomena, are observed in the case of no AC voltage control.

without the AC voltage control exhibit an oscillatory response with growing amplitude partly due to insufficiency of reactive power around this bus. Then, the orange line is terminated at about 0.42 s because the numerical integration stops due to the non-existence of trajectory satisfying the algebraic equations. This is observed in our previous paper [8] and results from the singularity of the algebraic equations. On the other hand, the blue line, namely, the voltage dynamics with the AC voltage control exhibit a damped oscillation, where the AC voltage control works effectively. For the small increase in Fig. 3b, both the orange and blue lines can be extended up to 1 s, and a slight decrease of voltage amplitude is observed for the case without the AC voltage control. Figure 4 shows the main result of this paper—load margin for short-term voltage stability. The blue bar graphs represent the load margin for the AC/MTDC system with the AC voltage control, and the orange bar graphs do that without the AC voltage control. From these graphs, the AC voltage control improves the load margin by 39 MW (in average) for increase of active power and by 27 Mvar (in average) for reactive power. Here, the rated power and power factor of the synchronous generator connected to 3 (in Fig. 2.18 of [10]) in the AC system, are 128 MVA and 0.85, and hence the rated active power and reactive power are 109 MW and 67 Mvar. In this sense, we conclude that 39 MW/109 MW × 100% = 36% and 27 MW/67 Mvar × 100% = 40% of the related outputs of the generator can be realized with the AC voltage control, namely, without harnessing the AC system. This presents a quantitative evidence of the benefit of AC voltage control for enhancement of short-term voltage stability of the interconnected AC/MTDC system.

4. Conclusion
This paper numerically evaluated the short-term voltage stability of the rudimental interconnected AC/MTDC system with emphasis on AC voltage control of VSC. The AC/MTDC system consisted of the IEEE 9-bus system and VSC-based MTDC system with all-to-all coupling. Numerical simulations
Fig. 4. Load margin for step increase of load in active and reactive power. The increase of load margin by introducing the AC voltage control, which is the difference between the blue and orange bars on each bus, is confirmed. The location of buses 5, 6, and 8 is confirmed in Fig. 2.18 of [10].

of the nonlinear DAE model were conducted for determining the load margin of short-term voltage stability of the AC/MTDC system. The simulations show that the AC voltage control increases the load margin on active power and reactive power, indicating a clear benefit of the AC voltage control on enhancing the short-term voltage stability.

Many follow-up studies to the present paper are possible. One is to evaluate the effect of the droop controller in Fig. 2a on the short-term voltage stability. Another is to simulate dynamic responses against different sets of disturbances as the large-signal security assessment. The detailed evaluations will be reported as another paper.

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References
[1] N. Chaudhuri, B. Chaudhuri, R. Majumder, and A. Yazdani, Multi-terminal Direct-Current Grids: Modeling, analysis, and control, John Wiley & Sons, 2014.
[2] D. Jovcic and K. Ahmed, High Voltage Direct Current Transmission: Converters, Systems and DC Grids, John Wiley & Sons, 2015.
[3] P. Kundur et al., “Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions,” IEEE Transactions on Power Systems, vol. 19, no. 3, pp. 1387–1401, August 2004.
[4] N.R. Chaudhuri, R. Majumder, and B. Chaudhuri, “System frequency support through Multi-Terminal DC (MTDC) grids,” IEEE Transactions on Power Systems, vol. 28, no. 1, pp. 347–356, February 2013.
[5] F. Milano, F. Dörfler, G. Hug, D.J. Hill, and G. Verbič, “Foundations and challenges of low-inertia systems (Invited Paper),” Proc. 2018 Power Systems Computation Conference (PSCC), pp. 1–25, 2018.
[6] J.A. Suul, S. D’Arco, P. Rodríguez, and M. Molinas, “Impedance-compensated grid synchronisation for extending the stability range of weak grids with voltage source converters,” IET Generation, Transmission & Distribution, vol. 10, no. 6, pp. 1315–1326, April 2016.
[7] Y. Susuki, N. Kawamoto, Y. Ohashi, A. Ishigame, T. Funaki, and S. D’Arco, “A modular approach to large-signal modeling of an interconnected AC/MTDC system,” Proc. 2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), pp. 945–949, 2020.
[8] N. Kawamoto, Y. Susuki, and A. Ishigame, “Estimation of stability region for an interconnected AC/multi-terminal DC grid,” NOLTA, vol. 11, no. 4, pp. 610–623, October 2020.
[9] D. Mende, D.S. Stock, and L. Hofmann, “Implementation, verification and application examples of a mathematical optimization for grid operation in mixed AC/DC-systems,” in Cigre International Symposium, Session 5, 002, 2019.

[10] P.M. Anderson and A.A. Fouad, Power System Control and Stability, 2nd ed., New York: IEEE Press, 2003.

[11] F. Milano, Power System Modeling and Scripting, Springer, 2010.

[12] R. Sandano, M. Farrell, and M. Basu, “Enhanced master/slave control strategy enabling grid support services and offshore wind power dispatch in a multi-terminal VSC HVDC transmission system,” Renewable Energy, vol. 113, pp. 1580–1588, July 2017.

[13] J. Beerten, S. D’Arco, and J.A. Suul, “Identification and small-signal analysis of interaction modes in VSC MTDC systems,” IEEE Transactions on Power Delivery, vol. 31, no. 2, pp. 888–897, April 2016.

[14] F. Milano, “An open source power system analysis toolbox,” in IEEE Transactions on Power Systems, vol. 20, no. 3, pp. 1199–1206, August 2005.