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A novel VSC-HVDC link model for dynamic power system simulations

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ABSTRACT

This paper introduces a new RMS model of the VSC-HVDC link. The model is useful for assessing the steady-state and dynamic responses of large power systems with embedded back-to-back and point-to-point VSC-HVDC links. The VSC-HVDC model comprises two voltage source converters (VSC) linked by a DC cable. Each VSC is modelled as an ideal phase-shifting transformer whose primary and secondary windings correspond, in a notional sense, to the AC and DC buses of the VSC. The magnitude and phase angle of the ideal phase-shifting transformer represent the amplitude modulation ratio and the phase shift that exists in a PWM converter to enable either generation or absorption of reactive power purely by electronic processing of the voltage and current waveforms within the VSC. The mathematical model is formulated in such a way that the back-to-back VSC-HVDC model is realized by simply setting the DC cable resistance to zero in the point-to-point VSC-HVDC model. The Newton–Raphson method is used to solve the nonlinear algebraic and discretised differential equations arising from the VSC-HVDC, synchronous generators and the power grid, in a unified frame-of-reference for efficient, iterative solutions at each time step. The dynamic response of the VSC-HVDC model is assessed thoroughly; it is validated against the response of a detailed EMT-type model using Simulink®. The solution of a relatively large power system shows the ability of the new dynamic model to carry out large-scale power system simulations with high efficiency.

1. Introduction

Continuous increases in electrical energy consumption have encouraged a great deal of technological development in the electrical power industry. In particular, the development of new equipment for power transmission that enables a more flexible power grid aimed at achieving higher throughputs, enhancing system stability and reducing transmission power losses, has been high on the agenda [1,2]. The VSC-HVDC link is the latest equipment developed in the arena of high-voltage, high-power electronics and its intended function is to transport electrical power in DC form, as well as to enable the asynchronous interconnection of otherwise independent AC systems [3], and to provide independent reactive power support. The technology employs Insulated Gate Bipolar Transistors (IGBTs), driven by pulse width modulation (PWM) control. This valve switching control permits to regulate dynamically, in an independent manner, the reactive power at either terminal of the AC system and the power flow through the DC link [4].

The VSC-HVDC model put forward in this paper comprises two VSC models linked by a cable on its DC sides. In turn, each VSC model is made up of an ideal phase-shifting transformer which synthesises the phase-shifting and scaling nature of the PWM control. The ideal phase shifter is taken to be the interface between the AC and DC circuits of the VSC. The model makes provisions for the representation of conduction losses and switching losses. Since both converters are capable of independently controlling the reactive power exchanged with the AC power grid at their respective AC nodes, the VSC-HVDC dynamic model uses two independent dynamic voltage regulators. Both control loops are aimed at providing the required reactive power support at their respective AC nodes to maintain pre-set voltages, by regulation of their amplitude modulation coefficients. Likewise the model correctly accounts for the dynamics of the DC link. This is carried out by using a control block that acts upon the DC current to adjust the DC voltage of the VSC-HVDC link.

It should be mentioned that in an early model of the VSC-HVDC system, the two VSC are emulated by idealised voltage sources [5–8]. Alternatively, the VSCs have also been represented by equivalent controlled current sources [9,10], where the currents to be injected into the AC grids are computed by the existing difference between the complex voltages of the VSC terminals and the AC

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system nodes at which the VSC-HVDC is embedded. More recently, the concept of dynamic average modelling has caught the attention of the power system community since it allows the modelling of VSCs in a more detailed manner [11]. In the dynamic average modelling approach, the average value of the output voltage waveform is calculated at each switching interval, a value that changes dynamically depending on the value of the reference waveform. The VSC is represented by a three-phase controlled voltage source on its AC sides and as a controlled current source on its DC sides [12]. However, this approach may be time consuming when repetitive simulations studies are required, such as in power grid expansion planning and in operation planning. The solution time is always an important point to keep in mind and in this method, increasing time steps is always a temptation but caution needs to be exercised when using the dynamic averaging method since, as reported in [12], the use of large time steps may affect the accuracy of the results. It is worth mentioning that if harmonics or electromagnetic transients are the study subject, such a high level of modelling detail is necessary, where, for instance, the PWM control needs to be modelled explicitly to achieve meaningful results.

On the other hand, in large-scale power system applications, it looks attractive to represent each VSC as a controlled voltage source owing to its much reduced complexity. However, its internal variables may not be readily available. In contrast, the new model introduced here captures very well the key operational characteristics of the VSCs making up the HVDC link. This is done by using explicit state variables that encapsulate the actual performance of the AC and DC circuits for both, the steady-state and dynamic operating regimes. Furthermore, the new VSC-HVDC model possesses the four degrees of freedom found in actual VSC-HVDC installations, characterised by having simultaneous voltage support at its two AC terminals, DC voltage control at the inverter converter and regulated DC power at the rectifier converter.

The numerical implementation of the VSC-HVDC model is carried out using a unified framework which suitably combines the algebraic and discretised differential equations of the VSC-HVDC link model, the synchronous generators and the non-linear algebraic equations of the power grid. This iterative solution takes advantage of the Newton–Raphson (NR) method thus facilitating the efficient solution of the non-linear equations. The discretisation of the differential equations is carried out using the implicit trapezoidal rule of integration which has been proven to be numerically stable and accurate [13,14]. In this paper, special attention is paid to the new dynamic VSC-HVDC model, emphasising how the algebraic and discretised differential equations are assembled together in this framework.

2. VSC-HVDC model for dynamic analysis

2.1. Key physical characteristics

If two VSC stations are linked as shown in Fig. 1, a VSC-HVDC system is formed and termed point-to-point configuration. In this arrangement, electric power is taken from one point of the AC network, converted to DC in the rectifier station, transmitted through the DC link and then converted back to AC in the inverter station

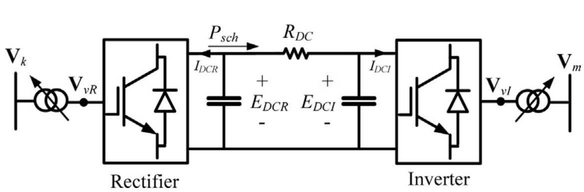

Fig. 1. Schematic representation of a VSC-HVDC link.

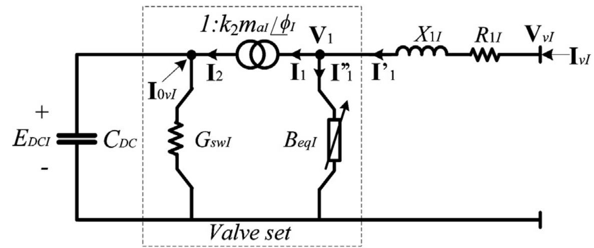

Fig. 2. VSC equivalent circuit for the inverter station.

and injected into the receiving AC network. In addition to transport power in DC form, this combined system is also capable of supplying reactive power and providing independent dynamic voltage control at its two AC terminals. It is worth mentioning that by setting the cable resistance R_{DC} to zero, the representation reduces to that of the so-called back-to-back VSC-HVDC configuration. Please refer to the Appendix A for the symbols used in all equations and figures.

2.2. VSC-HVDC steady-state model

Fig. 2 depicts the equivalent circuit of the VSC corresponding to the inverter station; a similar topology can be formulated for the rectifier station. Its steady-state representation relies on an ideal phase-shifting transformer with complex taps, a series impedance on its AC side as well as an equivalent variable shunt susceptance B_{eqI}, and a shunt resistor on its DC side [15].

The series reactance X_{1I} represents de VSC's interface magnetics whereas the series resistor R_{1I} is associated to the ohmic losses which are proportional to the AC terminal current squared. The shunt resistor (with a conductance value of G_{swI}) produces power loss to account for the switching action of the converter valves. This conductance is calculated according to rated conditions and ensures that the operating conditions on switching losses are represented by scaling the quadratic ratio of the actual terminal current I_I to the nominal current I_{nom} : $G_{swI} = G_{0I}\left(I_I/I_{nom}\right)^2$. Note that the squaring of this ratio is to give the switching conductance term an overall power performance. The following assumptions are made in the model: (a) the complex voltage $V_1 = k_2 m_{aI}\, E_{DC} e^{j\phi I}$ is the voltage relative to the system phase reference; (b) the tap magnitude m_{aI} of the ideal phase-shifting transformer corresponds to the VSC's amplitude modulation coefficient where the following relationship holds for a two-level, three-phase VSC : $k_2 = \sqrt{3/8}$; (c) the angle ϕ_I is the phase angle of voltage V_1; (d) E_{DC} is the DC bus amplitude voltage which is a real scalar. Bearing this in mind, the nodal power flow equations for the series branch of the VSC representing the inverter station are derived from the nodal admittance matrix developed in Appendix B. After some arduous algebra, the active and reactive powers expressions for the powers injected at both ends of the VSC, nodes vI and $0vI$, are arrived at:

$$P_{vI} = V_{vI}^2 G_{1I} - k_2 m_{aI} V_{vI} E_{DCI}\left[G_{1I}\cos\left(\theta_{vI}-\phi_I\right) + B_{1I}\sin\left(\theta_{vI}-\phi_I\right)\right] \quad (1)$$

$$Q_{vI} = -V_{vI}^2 B_{1I} - k_2 m_{aI} V_{vI} E_{DCI}\left[G_{1I}\sin\left(\theta_{vI}-\phi_I\right) - B_{1I}\cos\left(\theta_{vI}-\phi_I\right)\right] \quad (2)$$

$$\begin{aligned} P_{0vI} = {} & k_2^2 m_{aI}^2 E_{DCI}^2 G_{1I} - k_2 m_{aI} V_{vI} E_{DCI}\left[G_{1I}\cos\left(\phi_I-\theta_{vI}\right)\right. \\ & \left. + B_{1I}\sin\left(\phi_I-\theta_{vI}\right)\right] + P_{swI} \end{aligned} \quad (3)$$

$$\begin{aligned} Q_{0vI} = {} & -k_2^2 m_{aI}^2 E_{DCI}^2 B_{1I} - k_2 m_{aI} V_{vI} E_{DCI}\left[G_{1I}\sin\left(\phi_I-\theta_{vI}\right)\right. \\ & \left. - B_{1I}\cos\left(\phi_I-\theta_{vI}\right)\right] + Q_{eqI} \end{aligned} \quad (4)$$