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A novel power-flow model of multi-terminal VSC-HVDC systems

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ABSTRACT

This paper proposes a generalized framework for power-flow modeling of voltage-sourced converter (VSC) based multi-terminal high voltage DC (M-VSC-HVDC) network(s). The modeling strategy pertains to the point-to-point (PTP) HVDC network configuration, which is more generic and widely used than its back-to-back (BTB) counterpart. Unlike existing models, the modulation indices of the pulse width modulation (PWM) converters also appear as unknowns in the proposed model. In addition, both the HVDC network topology and the number of converters can be arbitrarily chosen in the generalized model. For the master converter, either the DC side voltage or the modulation index can be chosen as an unknown, which renders the model more versatile. Numerous case studies carried out by applying different control modes to varying topologies of M-VSC-HVDC networks incorporated in the IEEE-300 bus test system validate the model.

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1. Introduction

Since the last few decades, the construction of both generation facilities and in particular, new transmission lines have been delayed due to energy cost, environmental concerns, rights-of-way (RoW) restrictions and other legislative and cost problems. In this respect, HVDC transmission has proved to be a cost-effective option. For a given power level, a DC link requires a smaller RoW, simpler and cheaper transmission towers, reduced conductor and insulator costs along with reduced losses [1,2]. A HVDC link can also be used to improve system reliability by interconnecting two asynchronous AC systems. In addition, stability considerations limit the length of AC transmission links. No such limitation exists for HVDC transmission. All these led to the development of HVDC transmission systems.

The first commercial application of HVDC transmission took place between the Swedish mainland and the island of Gotland in 1954, using mercury-arc valves. Subsequently, the first 320 MW, thyristor based HVDC system was commissioned in 1972 between Canadian provinces of New-Brunswick and Quebec [2]. Over the years, developments in conversion equipment reduced their size and cost which resulted in more widespread use of HVDC transmission. This so-called line-commutated converter (LCC) based HVDC technology now constitutes the bulk of the installed DC transmission capacity over the world.

The advancement of power-electronics led to the development of insulated gate bipolar transistor (IGBT), which paved the way for VSC based HVDC technology. VSC-HVDC offered significant advantages over the LCC-HVDC like low cost and size of converter stations and reliable operation with weak AC systems. VSC-HVDC based on PWM scheme has the advantage of independent active and reactive power control, along with reduction in filter size [1–7]. Compact, modular design of the VSC facilitates rapid installation, commissioning and relocation. In recent years, the harnessing of renewable sources of energy is becoming an attractive and necessary option, in light of dwindling fossil fuel resources. The use of lighter and stronger cross linked poly-ethylene (XLPE) DC cables allows VSC based HVDC systems particularly attractive for offshore transmission. This has made possible the integration of offshore wind farms with AC grids and augments power transmission capacity.

Unlike a two-terminal HVDC interconnection, a M-VSC-HVDC system is more versatile and better capable of utilizing the economic and technical advantages of the VSC HVDC technology. It is also better suited if futuristic integration of renewable energy sources are planned [8–10].

In a M-VSC-HVDC system, the converters stations can be located closely, in the same sub-station or remotely, at different locations. The corresponding configurations are known as BTB or PTP, respectively. Most of the M-VSC-HVDC systems installed worldwide are in the PTP configuration, their DC sides being interconnected through DC links or cables.

In a M-VSC-HVDC system, one of the converters acts as a master or secondary converter [11] while the rest act as slave or primary converters. The master converter controls the voltage magnitude of its AC terminal bus while the slave converters control the active and

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List of symbols

$V_{DCg}, I_{DCg}, P_{DCg}$ DC voltage, current and power of the gth converter, respectively
m_g modulation index of the gth converter
Y_{ij} magnitude of the element in the ith row and jth column of the bus admittance matrix
ϕ_{ij} phase angle of the element in the ith row and jth column of the bus admittance matrix
R_{DCij} resistance of the DC link between DC buses '*i*' and '*j*'
$\mathbf{Y_{DC}}$ admittance matrix of the DC grid
Y_{DCij} element in the ith row and jth column of the admittance matrix of the DC network
$\mathbf{Z_{sh}}$ leakage impedance of the converter coupling transformer
R_{sh}, X_{sh} resistance and leakage reactance of the coupling transformer, respectively
V_i, θ_i bus voltage magnitude (rms) and phase angle at AC bus '*i*', respectively
V_{shg}, θ_{shg} magnitude (rms) and phase angle of the output voltage of the gth converter, respectively
P_{shg}, Q_{shg} active and reactive powers at the terminal end of the line connected to the gth converter, respectively

reactive powers at the terminal end of the lines connecting them to their terminal buses. Some excellent research works on control of VSC-HVDC systems are reported in [12–16].

Now, for planning, operation and control of AC power systems incorporating M-VSC-HVDC networks, suitable power-flow models of such hybrid systems is an essential requirement. [11,17–26] present some comprehensive power-flow and optimal power flow (OPF) models of VSC-HVDC systems. However, it is observed that most of the existing models do not take into account the modulation index of a converter. The modulation index '*m*' is an important parameter for VSC operation. It has been reported that although an increase in the amount of reactive power delivered by the VSC at the PCC bus requires a high value of '*m*', overmodulation ($m > 1$) results in low-order harmonics in the AC voltage spectrum [27]. For these reasons, usually, '*m*' should not exceed unity. In a similar manner, a low '*m*' limits the maximum fundamental AC side voltage of the VSC. Practical ranges of the modulation index '*m*' have been reported in [28].

Thus, operational considerations limit the minimum and maximum value of the modulation index. A power-flow model should yield the value of '*m*' and 'V_{DC}' directly, for a given operating condition, so that it can be checked whether '*m*' lies within its specified limits (with sufficient margin for a dynamic response), along with 'V_{DC}'. In the proposed model, the converter modulation indices appear as unknowns along with the converter DC side voltages and the phase angles of the converter AC side voltages. However, inclusion of the modulation index as an unknown does not exclude them from being effective control variables for the VSC operation. In this respect, it may be noted that control variables like tap settings of transformers and phase shifters along with converter control angles (firing angles of rectifiers or extinction angles of inverters) in LCC-HVDC have long been included as unknowns in Newton–Raphson Power-flow algorithms [29–31].

Furthermore, both the HVDC network topology and the number of converters can be arbitrarily chosen in the generalized model. This model also offers the flexibility of choosing either the DC side voltage or the modulation index of the master converter as an unknown. This renders the model more versatile. Due to the adoption of the AC–DC unified method, the quadratic convergence of the Newton–Raphson algorithm is retained in the proposed model.

Numerous case studies are carried out by applying different control modes to varying topologies of M-VSC-HVDC networks incorporated in the IEEE-300 bus test system [32]. The convergence features validate the proposed model.

The remainder of this paper is structured as follows: In Section 2, the mathematical modeling for the PTP M-VSC-HVDC is presented. Section 3 details the Newton power flow equations for the PTP M-VSC-HVDC system. The case studies and results are presented in Section 4. The conclusions are presented in Section 5.

2. Mathematical modeling of the PTP-M-VSC HVDC system

For the power flow modeling of a M-VSC-HVDC system, the following assumptions have been adopted [5,11].

- The supply voltages are sinusoidal and balanced (contain only fundamental frequency and positive sequence components).
- The harmonics generated by the converters are neglected.
- The switches are assumed to be ideal.

In the rest of the paper, bold quantities represent complex variables and matrices while regular variables denote scalar variables. All the transmission lines are represented by their equivalent-pi models.

Fig. 1 shows a '*n*' bus AC power system network incorporating a M-VSC-HVDC system, which is interconnected in the PTP configuration. The M-VSC-HVDC comprises '*p*' converters which are connected to '*p*' AC buses through their respective coupling transformers. Without loss of generality, it is assumed that the '*p*' VSC converters are connected to AC buses '*i*', '$(i+1)$', and so on, up to bus '$(i+p-1)$'. The equivalent circuit of Fig. 1 is shown in Fig. 2.

In Fig. 2, the VSCs are represented by '*p*' fundamental frequency, positive sequence voltage sources. The gth ($1 \le g \le p$) voltage source $\mathbf{V_{shg}}$ (not shown) is connected to AC bus '$(i+g-1)$' through the leakage impedance $\mathbf{Z_{shg}} = R_{shg} + jX_{shg}$ of the gth coupling transformer.

Now, let $\mathbf{y_{shg}} = 1/\mathbf{Z_{shg}}$. Then, from Fig. 2, the current through the gth ($1 \le g \le p$) coupling transformer can be written as

$$\mathbf{I_{shg}} = \mathbf{y_{shg}} \left(\mathbf{V_{shg}} - \mathbf{V_{i+g-1}} \right) \quad (1)$$

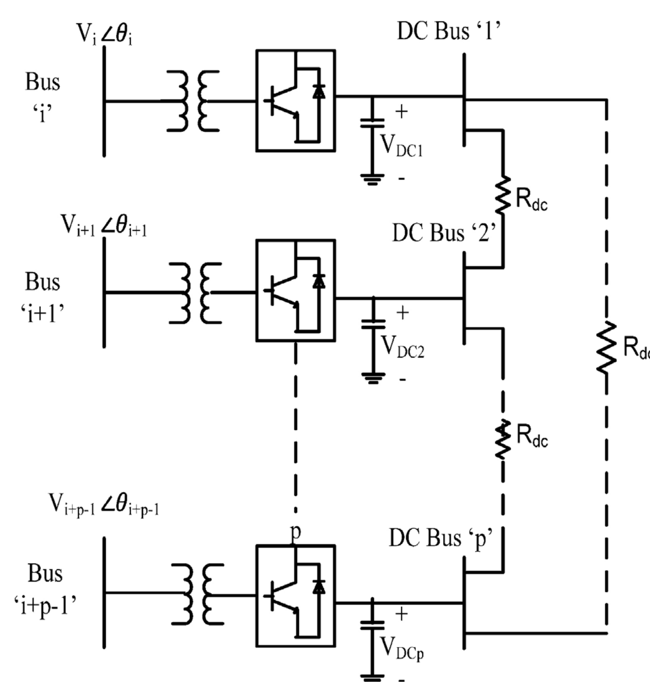

Fig. 1. Schematic diagram of a '*p*' terminal PTP M-VSC-HVDC system.

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