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Generalized power flow models for VSC based multi-terminal HVDC systems

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ABSTRACT

This paper presents a generalized Newton Raphson (NR) power flow model for voltage source converter (VSC) based multi-terminal HVDC (M-VSC-HVDC) systems. This model is applicable to both the back to back (BTB) and the point to point (PTP) M-VSC-HVDC configurations. The amplitude modulation indices of the PWM scheme and the converter DC voltage(s) appear as unknowns in the generalized model, which is developed from first principles. While the master converter controls the voltage magnitude at its AC terminal bus and maintains the converters' active power balance, the slave converters operate their terminal buses in the PV or PQ control modes. This model offers the flexibility of controlling either the DC voltage or the modulation index for the master converter. Numerous case studies carried out by applying different control strategies to various topologies of MTDC networks incorporated in the IEEE-118 bus test system validate the model.

Introduction

Over the years, ever increasing electricity demand has necessitated the requirement of increased transmission capacities by power utilities worldwide. This has been made possible by the development of voltage sourced converter (VSC) based HVDC technology with PWM control technique, employing IGBTs and GTOs. VSC based HVDC transmission systems facilitate the interconnection of asynchronous AC grids along with integration of renewable energy sources like offshore wind farms. PWM-VSC based HVDC transmission leads to fast and independent control of both active and reactive powers along with reduction in size and cost of harmonic filters [1–4]. Moreover, they are immune to the problems of commutation failure.

Depending on the locations of the converters, a VSC-HVDC system can have a Back to Back (BTB) or a point to point (PTP) configuration. In the Back to Back (BTB) scheme, the converters usually exist at the same location. On the other hand, in a point to point (PTP) scheme, the DC link is used to transmit the bulk power between converters which are at different locations [1–4].

The first 3-MW, VSC-HVDC link was commissioned at Hellsjon in Sweden in 1997. Subsequently, several VSC-HVDC projects have been installed in the U.S., Mexico, Australia, Sweden and Norway. This has led to increased interest in VSC-HVDC systems from both the academia and the utilities, worldwide. Although most of these VSC-HVDC interconnections are two-terminal, their modus operandi can also be extended to multi-terminal HVDC (MTDC) systems. Unlike a two-terminal HVDC interconnection, a MTDC system is more versatile and better capable to utilize the economic and technical advantages of the VSC HVDC technology. It is also better suited if futuristic integration of renewable energy sources are planned. A meshed HVDC interconnection between offshore wind farms and three asynchronous AC grids of the European Network of Transmission System Operators for Electricity (ENTSO-E) is being envisaged in the North Sea region [5–6].

For MTDC operation, one of the terminals is considered as a slack bus at which the DC voltage is specified. Depending on the control specifications adopted, a converter may be termed 'mas ter'/'slave' or 'primary'/'secondary' [7]. While a master or primary converter operates in the voltage control mode, a slave or secondary converter operates in the PQ or PV control mode. Refs. [8–11] present some excellent research works in the area of VSC-HVDC system controls.

Now, for planning, operation and control of a power system with multi-terminal VSC-HVDC (M-VSC HVDC) links, power flow solution of the network incorporating them are required. Thus, the development of suitable power flow models of M-VSC-HVDC systems is a fundamental requirement. Refs. [12–18] present some comprehensive research works in the area of Newton power-flow modelling of VSC-HVDC systems. Angeles-Camacho et al. [12]

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Nomenclature

V_{dc}, I_{dc}	DC voltage and current, respectively
$V_{dci}, V_{dcj}, V_{dck}$	DC voltages of converters connected to buses "*i*", "*j*" and "*k*" respectively
$I_{dci}, I_{dcj}, I_{dck}$	DC currents of converters connected to buses "*i*", "*j*" and "*k*" respectively
$P_{dci}, P_{dcj}, P_{dck}$	DC powers of converters connected to buses "*i*", "*j*" and "*k*", respectively
m_i, m_j, m_k	modulation indices of the converters connected to buses "*i*", "*j*" and "*k*" respectively
Y_{ij}	magnitude of element in the *i*th row and *j*th column of the bus admittance matrix
ϕ_{ij}	phase angle of element in the *i*th row and *j*th column of the bus admittance matrix
R_{dc}	resistance of the DC link
$\mathbf{Y_{dc}}$	admittance matrix of the DC grid
Y_{dcij}	element in the *i*th row and *j*th column of the admittance matrix of the DC network
$\mathbf{Z_{sh}}$	impedance of the converter coupling transformer
R_{sh}, X_{sh}	resistance and leakage reactance of the coupling transformer, respectively
V_i, V_j, V_k	AC bus voltage magnitudes (rms) at buses "*i*", "*j*" and "*k*" respectively
$\theta_i, \theta_j, \theta_k$	phase angles (degree) of AC voltages at buses "*i*", "*j*" and "*k*" respectively
$V_{shi}, V_{shj}, V_{shk}$	output voltage magnitudes (rms) of converters connected to AC terminal buses "*i*", "*j*" and "*k*", respectively
$\theta_{shi}, \theta_{shj}, \theta_{shk}$	phase angles (degree) of output voltages of converters connected to AC terminal buses "*i*", "*j*" and "*k*", respectively
$P_{shi}, P_{shj}, P_{shk}$	active powers in the lines connecting buses '*i*', '*j*' and '*k*' to the corresponding converters respectively
$Q_{shi}, Q_{shj}, Q_{shk}$	reactive powers in the lines connecting buses '*i*', '*j*' and '*k*' to the corresponding converters respectively
NI	number of iterations

presents a VSC-HVDC mathematical model suitable for direct incorporation into existing Newton–Raphson power flow programs. However, the analysis of [12] is limited to a two terminal HVDC system. A multi-terminal VSC-HVDC power flow model suitable for both the BTB and the PTP configurations is presented in [13]. However, it does not explicitly address the inclusion of the modulation index as an unknown. Although [14,15] extend the realm of VSC-HVDC modelling to optimal power flow, the analyses are again limited to two terminal systems. A steady-state VSC MTDC model including DC grids with arbitrary topologies is reported in [16]. However, due to the adoption of the sequential power flow algorithm, Beerten et al. [16] fails to exploit the quadratic convergence characteristics of the Newton–Raphson method. Acha et al. [17] presents a comprehensive VSC-HVDC Newton power flow model which treats the VSCs as compound transformer devices and takes into account the phase shifting and scaling nature of PWM control, inclusive of VSC inductive and capacitive power design limits along with switching and ohmic losses. However, this paper does not address exclusively the modelling of multi-terminal VSC-HVDC systems. Wang and Barnes [18] presents a novel power flow approach for MTDC systems with different network topologies incorporating different DC voltage strategies. However, this model does not address exclusively the treatment of the converter modulation indices as unknowns. Also, the quadratic convergence characteristics of the unified AC/DC Newton-Raphson algorithm is sacrificed due to the sequential iterative solution adopted.

This work discusses the modelling of a M-VSC-HVDC system with arbitrary DC grid topologies for incorporation in an existing AC power flow model. In this model, the amplitude modulation indices of the PWM scheme along with the DC side voltages of the converters appear as unknowns. This is an advantage over most of the existing models [12,13,15,16,18] as the modulation index '*m*' is an important parameter for VSC operation. While a low '*m*' limits the maximum fundamental VSC AC side voltage, over modulation ($m > 1$) results in low-order harmonics in the AC voltage spectrum [19,20]. Additionally, this model offers the flexibility of controlling either the modulation index or the DC side voltage for the master converter. Two mathematical models for the M-VSC HVDC are presented in this work. While the first model represents a Back to Back (BTB) M-VSC-HVDC system, the second one pertains to a point to point (PTP) M-VSC-HVDC system. In both the models, for control of the DC links, multiple control modes are implemented. Numerous case studies carried out by applying different control strategies to varying topologies of MTDC networks incorporated in the 118-bus test system validate the proposed model.

The remainder of this paper is organized as follows: In Section 'Modelling of a BTB M-VSC HVDC system', the mathematical modelling of the Back to Back M-VSC-HVDC is presented. Section 'Newton power flow equations of the BTB M-VSC-HVDC system' details the Newton power flow equations for the BTB M-VSC-HVDC. In Section 'Modeling of the PTP-M-VSC HVDC system', the mathematical modelling for the point to point (PTP) M-VSC-HVDC is presented. Section 'Newton power flow equations of the PTP M-VSC-HVDC system' details the Newton power flow equations for the PTP M-VSC-HVDC system. The case studies and results are presented in Section 'Case studies and results'. The conclusions are presented in Section 'Conclusions'.

Modelling of a BTB M-VSC HVDC system

For the power flow modelling of a M-VSC-HVDC system, the following assumptions have been adopted [1–3].

- 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.

The schematic representation of a BTB M-VSC-HVDC system is shown in Fig. 1. From Fig. 1, it can be observed that three converters are shown connected to three AC buses '*i*', '*j*' and '*k*' via three converter transformers. All the converters are located at the same site and are interconnected through a common DC link. Fig. 2 shows the equivalent circuit of the network shown in Fig. 1. The converter connected to bus '*i*' is considered as a master converter, while the converters connected to buses '*j*' and '*k*' are considered slave converters. The master converter controls the terminal voltage of its AC bus i.e. bus '*i*' and also balances the active power exchange among the converters.

In Fig. 2, let $\mathbf{Z_{shn}} = R_{shn} + jX_{shn}$ $(n = i, j, k)$ be the impedance of the converter coupling transformer, where R_{shn} and X_{shn} represent its resistance and leakage reactance, respectively. Then, from Fig. 2, the current in the line connecting the AC terminal bus '*n*' $(n = i, j, k)$ to its respective converter can be computed to be