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Harmonic power flow of VSC-HVDC based AC/DC power systems

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ABSTRACT

This paper extends the traditional harmonic power flow (HPF) to include voltage source converter (VSC) based HVDC. First, a new harmonic model of VSCs, called the real harmonic coupling matrix (RHCM), is developed. The real-valued model is simple in form and easy to calculate. The nonlinear relationship between harmonics and VSC control variables is analytically represented. Then, the model is used to integrate VSC-HVDC into the rectangular-form HPF. Newton's method is adopted to simultaneously solve the AC and DC system harmonics and fundamental power flow. The algorithm is validated by time-domain simulation and tested on a 10-bus AC/DC power system. The effect of VSC harmonics on fundamental power flow is investigated, so is the effect of different operating conditions on harmonics. The results demonstrate that the proposed HPF makes a very useful tool in the harmonic analysis of VSC-HVDC based AC/DC power systems.

1. Introduction

With the rapid development of turn-off semiconductor devices, voltage source converters (VSCs) have been increasingly employed in FACTS and HVDC systems [1]. Compared with conventional thyristor-based technology, the VSC-based HVDC has many favourable technical advantages and is very promising in renewable energy integration, transmitting power to weak AC systems, urban electricity supply, etc. [2,3].

One of the most challenging problems of VSC-HVDC is the harmonic distortion. Although the advances in pulse width modulation (PWM) techniques and multi-level topologies [3] have partly reduced the severity of the problem, still the AC–DC conversion of VSCs generates a lot of harmonics [4] that harm the power systems in many aspects. The problem deserves more attention as the voltage and power levels of VSC-HVDC keep increasing. It is therefore important to include harmonics in the steady-state analysis of VSC-HVDC based AC/DC power systems.

Regarding the harmonic analysis of VSC-HVDC, existing literature is mainly focused on harmonic impedance analysis and DC system harmonic responses [4–6]. In [7], the harmonic interaction between the AC and DC sides of VSC-HVDC was studied. But the effect of fundamental-frequency power flow was not taken into account. Until now, no published work has been found to deal with the inclusion of VSC-HVDC in the harmonic power flow (HPF) algorithm [8]. To accurately compute the AC and DC side harmonics and facilitate a deeper understanding of the interaction between the harmonics and fundamental power flow, the traditional HPF should be modified to include VSC-HVDC subsystems. The HPF of line-commutated converter (LCC) based AC/DC power systems has been studied extensively [9–12]. In [12], three-phase power flow and converter harmonics were solved together using Newton's method. AC system unbalance and non-characteristic harmonics were also taken into account. In fact, many of the successful HPF algorithms simultaneously solve the fundamental power flow and converter harmonics. Such a unified Newton solution framework yields more reliable results than direct methods (Ybus/Zbus methods) [13] which are normally based on over-simplified linear harmonic models. Moreover, the unified framework exhibits better convergence than separate ones where the fundamental power flow and converter harmonics are solved in a sequential (decoupled) manner [12]. Hence, this paper adopts the unified Newton solution framework. The VSC-HVDC HPF is developed by directly integrating the harmonic model of VSCs into the HPF of balanced AC/DC power systems. The resulting nonlinear HPF equations are then solved by Newton's method.

The harmonic model of VSCs is essential to the proposed HPF. Like traditional converters, the harmonic modelling process can be done in frequency or time domain [13–18]. In recent years, a wide variety of VSC harmonic models have been established [19–24]. Closed-loop models considering control have also been available [20–22]. Most of them are based on complex-form Fourier series (discrete-form Fourier transform). While these models have been proven to be sufficiently accurate in the harmonic analysis of

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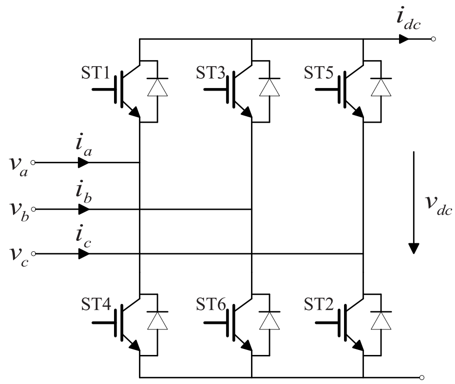

Fig. 1. Schematic diagram of the three-phase two-level VSC.

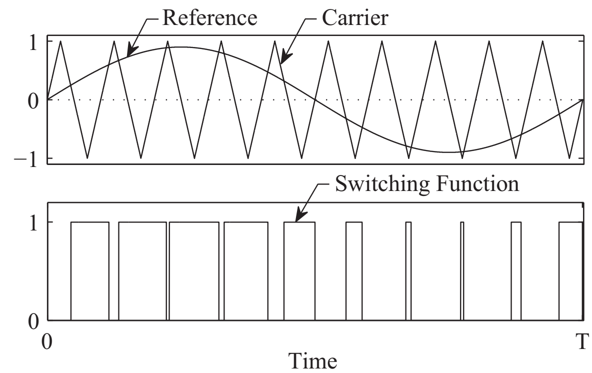

Fig. 2. NSPWM process of ST1 ($m_f = 10$).

individual converter systems, they are complex-valued and inevitably involve negative-order harmonics. Difficulties can be met when one tries to directly employ them in power system HPF algorithms which are actually implemented in real arithmetic. In real and positive-order harmonic domain, however, the combination of VSC harmonic models and the HPF can be achieved easily. Therefore, this paper presents a new harmonic model of VSCs called the real harmonic coupling matrix (RHCM), which is based on trigonometric-form Fourier series and piecewise-constant switching functions. It only involves positive-order harmonics, and is naturally real-valued, simple in form, and easy to calculate. The nonlinear relationship between the VSC harmonics and the PWM control variables is analytically represented. All these features render the model very suitable for the proposed VSC-HVDC HPF. Another real-valued harmonic modelling approach is the one based on Harley transform, which is elegant in math and efficient in computation [25,26]. It is, however, not adopted in this paper mainly because the Hartley transform uses the term "cas" rather than "cos" or "sin" to define harmonics and is thus considered a bit too abstract.

We use the rectangular coordinate system instead of its polar alternative to formulate the entire VSC-HVDC HPF. The primary considerations are that the trigonometric-form Fourier series and the derived RHCM are inherently in rectangular form and the algorithm is easier to implement. Further comparative studies of the performance of the rectangular- and polar-form HPF are still required. In addition, the applicability of rectangular coordinates in other HPF variants such as the probabilistic harmonic load flow [27] also needs further investigations.

The main contributions of the paper are: (1) a new harmonic model of VSCs suitable for HPF algorithms is presented; (2) the rectangular-form HPF is formulated for balanced AC/DC power systems containing VSC-HVDC; (3) the VSC-HVDC HPF is solved using the unified Newton's method with the Jacobian analytically formed; (4) the proposed algorithm is tested and used to analyse the effect of VSC harmonics on fundamental power flow as well as the effect of different VSC-HVDC operating conditions on harmonics. The paper is organized as follows. Section 2 presents the VSC harmonic model. The VSC-HVDC HPF is formulated in Section 3. Section 4 deals with the Newton solution. In Section 5, the algorithm is first validated by time-domain simulation and then applied to the harmonic analysis of a 10-bus AC/DC power system. Section 6 concludes the work.

2. Harmonic model of VSCs

Fig. 1 shows the schematic diagram of a three-phase VSC with the typical two-level topology adopted by most of the existing VSC-HVDC systems. The sinusoidal reference signal is of fundamental frequency ω_1 and the carrier (switching) frequency $\omega_c = m_f\omega_1$, where m_f is the frequency modulation ratio. By adjusting the phase angle δ and the amplitude modulation ratio m_a of the reference signal, we can independently control the active and reactive power transferred through the converter from the AC to the DC side or vice versa.

Before the derivation of the harmonic model, the following assumptions are made: (1) the three phases are balanced; (2) all valves are ideal which means they can be switched on and off instantaneously and do not cause any switching losses.

2.1. Switching instants and switching functions

Suppose that the natural sampled PWM (NSPWM) is used. Fig. 2 illustrates the NSPWM process associated with ST1 in phase a of the VSC. The upper switches in the other two phase-legs go through the same processes except the reference signals are delayed by 120° and 240°, respectively.

The switching instants are generated by the intersection of the reference and carrier signal waveforms. Let n_{sw} be the number of switching instants of a switch in one fundamental cycle T_1. From Fig. 2, $n_{sw} = 2m_f$. The switching instants t_k ($k = 1, 2, \ldots, n_{sw}$) of ST1 are determined by

$$f_r(t_k) - f_c(t_k) = 0 \tag{1}$$

where $f_r(t) = m_a \sin(\omega_1 t + \delta)$ is the reference signal of phase a and $f_c(t)$ is the triangular carrier signal.

Eq. (1) is nonlinear and can be readily solved by Newton's method. The only tricky part is choosing the initial value for each t_k, which can be done by uniform sampled PWM [28]. Numerical tests showed that the solution generally converged in 2–3 iterations with a tolerance of 10^{-12} s.

With the switching instants known, the switching functions [19] can be obtained. We can thereby write the equations of the current and voltage relationships between the AC and DC sides of the VSC.

For the currents,

$$i_{DC}(t) = \sum_{p \in \{a,b,c\}} s_p(t) \cdot i_p(t) \tag{2}$$

where $i_{DC}(t)$ is the DC side current, $i_p(t)$ is the AC side phase-p current, and $s_p(t)$ is the phase-p switching function.

For the voltages,

$$v_{pm}(t) = s_{pm}(t) \cdot v_{DC}(t), \quad p, m \in \{a, b, c\} \tag{3}$$

where $v_{pm}(t)$ is the AC side line-to-line voltage, $v_{DC}(t)$ is the DC side voltage, and $s_{pm}(t) = s_p(t) - s_m(t)$.

The time-domain behaviour of the open-loop VSC can be completely described by (2) and (3), whose transformation into frequency (harmonic) domain yields the VSC's harmonic model.