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Control Energy Consumption and System Performance in Vector Control of Voltage Source Converters

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Abstract: Power electronics plays an important role in the control and conversion of modern electric power systems. In particular, to integrate various renewable energies using DC transmissions and to provide more flexible power control in AC systems, significant efforts have been made in the modulation and control of power electronics devices. Pulse width modulation (PWM) is a well developed technology in the conversion between AC and DC power sources, especially for the purpose of harmonics reduction and energy optimization. As a fundamental decoupled control method, vector control with PI controllers has been widely used in power systems. However, significant power loss occurs during the operation of these devices, and the loss is often dissipated in the form of heat, leading to significant maintenance effort. Though much work has been done to improve the power electronics design, little has focused so far on the investigation of the controller design to reduce the controller energy consumption (leading to power loss in power electronics) while maintaining acceptable system performance. This paper aims to bridge the gap and investigates their correlations. It is shown a more thoughtful controller design can achieve better balance between energy consumption in power electronics control and system performance, which potentially leads to significant energy saving for integration of renewable power sources.

Keywords: VSC; renewable energy; power loss; system performance; PI controller;

1. INTRODUCTION

To meet more stringent legislations on environment protection while to offer new alternative solutions to non-renewable fossil fuel, various renewable energies are promised to be integrated to existing AC power systems, especially the integration of off-shore wind farms (Association et al. [2005]). The integration of renewable energy sources into the existing electrical grid has brought forward several technical challenges which necessitate the adoption of high voltage direct current (HVDC) transmission lines that draw little capacitive current compared with high voltage alternate current (HVAC) solutions. Voltage source converters (VSC), working as an interface between DC and AC networks, offer a number of advantages in comparison with traditional line commutated converters (LCC). For example, VSC using high voltage IGBT is capable of switching at a higher operating frequency, and VSC-HVDC can achieve independent control of active and reactive powers, fast and reversible control of power flow, and asynchronously decoupling with AC grids.

The operation and control of VSCs have been well researched in the literature. Popular approaches include model predictive control (Vargas et al. [2007]), voltage oriented vector control (Cortes et al. [2008]). Voltage oriented control (VOC), which guarantees high dynamic and static performances via an internal current control loop, has become very popular in recent years (Kaźmierkowski and Krishnan [2002]).

As a commonly used modulation technique for controlling power electronic devices, PWM is fundamental for the VSC operation, including sinusoidal pulse width modulation, space vector PWM, etc. (Moustafa [2011]). Further, a number of researches have been carried out on harmonics reduction and energy optimization in power electronics control (Holtz and Qi [2013], Wiechmann et al. [2008], Chung and Sul [1999], Kolar et al. [1991]). However, these researches mainly focus on the PWM structure design to reduce the power loss during switching operation and on vector control tuning to achieve better system dynamic performance. Although the PWM control frequency can be optimized to reduce power losses, little has been done so far on investigating the correlation between vector control parameter design and power loss reduction, and how the controller design can help to reduce the power loss in power electronics and in the meantime, maintaining desirable system performance.

It is well known that significant power loss occurs during the operation of these devices, and the loss is often dissipated in the form of heat, leading to remarkable main-

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tenance effort. Therefore it is essential to investigate the power loss and its relation to system real-time operation and control, thus guiding the proper design of the controller used in the system. This paper aims to bridge the gap and it is shown a more thoughtful controller design can achieve better balance between energy consumption in power electronics control and system control performance, which potentially leads to significant energy saving in power electronics control for integration of renewable power sources. It shows that this relation is non-linear and a better controller design can achieve a good trade-off between power loss and system performance.

This paper is organized as below. In section II, the VSC module and vector control method are outlined. Power consumption study of a VSC due to different controller designs is carried out in Section III. In Section IV, the correlation between controller energy consumption and system performance is analysed for DC voltage controller and current loop controller. In Section V, simulation results based on Matlab/Simulink are carried out to validate the proposed design method. Finally, conclusion is drawn in Section VI.

2. VSC MODEL AND VECTOR CONTROL

In this paper, a generic two level three phase converter bridge as shown in Fig. 1 is investigated. There are two

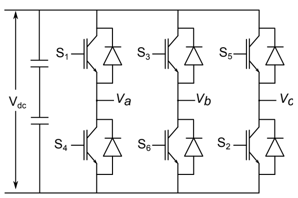

Fig. 1. Two level three phase voltage source converter

IGBTs and diodes in each phase. Every IGBT works with the opposite diode during a half AC cycle. The switching pulse signals for IGBTs are provided by a PWM modulator. Thus the main purpose of the vector controller can be treated as providing a reference for the modulator.

The basic structure of the VSC vector controller includes two feedback loops: an inner current loop supplies signals for PWM modulator to provide gate signals for IGBT, and an outer voltage loop regulates the DC voltage or active power and provides the current reference. The overall diagram of the VSC controller is shown in Figure 2.

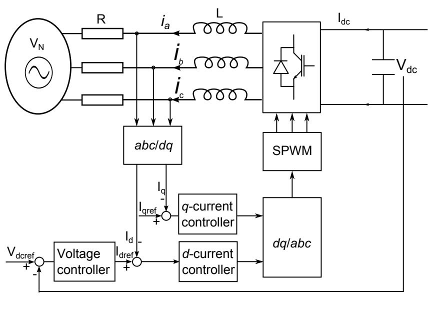

Fig. 2. Basic control scheme of VSC

In this paper, the inner current controller and the DC voltage controller are analysed and designed considering both system performance and power losses.

2.1 Inner current controller

Applying the commonly used vector conversion method, every set of three phase voltages and currents can be represented by a rotating vector respectively, using their instantaneous values. The d-axis of the rotating frame is in phase with the voltage phasor at the point of common coupling (PCC). In this way the q-axis component of the voltage becomes zero. After the abc/dq transformation, the AC side circuit equation takes the form of (1).

$$\begin{aligned} L\frac{di_d}{dt} + Ri_d = V_{Cd} - V_{Nd} + \omega Li_q \\ L\frac{di_q}{dt} + Ri_q = V_{Cq} - V_{Nq} - \omega Li_d \end{aligned} \tag{1}$$

The operation of VSC requires i_d and i_q to follow varying reference points. So currents of i_d and i_q can be controlled independently by acting on a set of auxiliary inputs as

$$u_d = L\frac{di_d}{dt} = k_{p1}(i_d^* - i_d) + k_{i1}\int(i_d^* - i_d)dt \tag{2}$$

where k_{p1} and k_{i1} are the proportional and integral gains of the current controller. The PI controller of d and q-axis can be set using the same parameters. The output of the PI controller compensate voltage drops on the reactor and the feed forward of AC network voltage can respond to the AC network voltage change. After decoupling, the current control loop can be simplified as shown in Figure 3. The open loop transfer function of the inner current loop can be derived as,

$$G_{open} = (K_p + \frac{K_i}{s})\frac{e^{-1/f_p s}}{sL + R} \tag{3}$$

It is clear that the close loop transfer function can be drawn as a second order system if the time delay is small enough to be omitted.

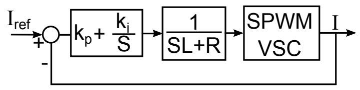

Fig. 3. Simplified inner current control loop

2.2 DC voltage controller

For a typically DC voltage regulating terminal, VSC on the DC side can be modelled as a controlled current source, as shown in Fig. 4.

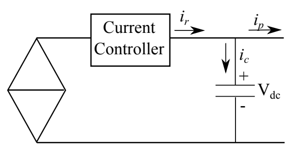

Fig. 4. VSC DC side model

A PI controller is normally used to control the DC voltage at a desired level for the DC voltage regulator. The output