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Direct power control of a multilevel inverter based active power filter

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Abstract

A cascaded H-bridge multilevel inverter based active power filter with a novel direct power control is proposed in this paper. It can be directly connected to medium/high voltage power line without using the bulky transformer or passive filter. Due to the limited switching frequency (typically below 1 kHz) of high-power solid-state devices (GTO/IGCT), multiple synchronous/stationary reference frame current controllers are reviewed and derived. Based on this, a novel current controller is proposed for harmonic current elimination and system power factor compensation. Furthermore, a synchronous/stationary hybrid structure can be derived with fundamental de-coupling control. The instantaneous reactive power theory and synchronous reference frame based control are compared based on mathematical models. A direct power control concept is then derived and proposed. It is equivalent as the hybrid synchronous/stationary frame current controller, but has a simpler implementation. It has clear physical meaning and can be considered as a simplified version of the hybrid frame current controller. Simulations on a 4160 V/1.2 MVA system and experimental results on a 208 V/6 kVA laboratory prototype are presented to validate the proposed active power filter design.

Keywords: Active power filter; Medium voltage; IGCT; Direct power control; Current control; Low switching frequency

1. Introduction

Voltage source inverter based parallel active filter is known for current harmonic compensation of the power system and have been widely studied by using high switching power device (IGBT) [1]. For medium/high voltage application, a direct connected active filter can be more attractive by eliminating the bulky transformer or passive filter. Due to the limited switching frequency (typically below 1 kHz) of high-power solid-state devices (GTO/IGCT), multilevel inverters have to be used [2]. This paper proposed a cascaded H-bridge multilevel inverter based active filter. Multiple techniques are studied to increase the system bandwidth at low switching frequency:

- First, a software based multiple-sampled phase shifted PWM is proposed.
- Secondly, among most current controller designed for active filters, multiple synchronous reference frame based current controller is proven to have the highest bandwidth with modest feedforward gain.
- Thirdly, an equivalent stationary frame based current controller is easily derived based on complex vector theory. The results are similar as that derived from convolution [3] or physical concept [4] in recent literature.
- Fourthly, to remove the fundamental cross-decoupling term in synchronous reference frame, a synchronous/stationary hybrid frame based current controller is proposed.
- Finally, instantaneous reactive power (IRP) theory [5] and synchronous reference frame (SRF) [6] based methods are briefly compared. The connections between them are explained. Based on these, an instantaneous reactive power theory based direct power control is derived from the synchronous/stationary hybrid frame based current controller.

This new concept combines the IRP theory and current control into one controller called direct power controller. The power reference is created by the IRP and a linear direct power controller is designed accordingly. It is similar to the multiple reference frame current controllers, which are suitable for high power/low switching frequency applications. Simulations on a 4160 V/1.2 MVA system are provided and the proposed theory is

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verified on a 208 V/6 kVA five-level cascaded H-bridge inverter based active power filter.

2. Cascaded H-bridge multilevel inverter based active power filter

2.1. Modular structure

In medium voltage/high voltage power electronics system design, there is a strong tendency to modularize the power pass and digital controller in order to reduce the price, simplify converter design and potentially increase the availability of applicable converters.

There are three main voltage source multilevel converter topologies—diode-clamped converter [7], flying capacitor converter [8] and cascaded H-bridge converter [9]. Among them, cascaded H-bridge topology is presented to be the best candidate for medium voltage active power filtering application due to its modular feature of offering the least component with easy extension to higher level system.

For active power filter application, the bandwidth of the multilevel converter has to be decided by the highest harmonic to be compensated. Generally, 5th, 7th, 11th and 13th are the dominant harmonics at the medium voltage power line. Considering the 500–700 Hz switching frequency of the medium voltage power device, a five level cascaded H-bridge inverter based active filter is proposed here. The system configure is shown in Fig. 1. The design is based on the medium voltage applications (2.3–13.8 kV). The converter is composed of six H-bridges and six dc capacitors. It is connected to the power line through a 5–10% per unit inductor only.

2.2. PWM method

Natural sampled PWM [10] is the best choice for applications that require closed loop control and wide bandwidth modulation, such as active power filtering. It does not attenuate or distort the modulating signal, even when the frequency of that signal is similar to the switching frequency. Carrier based PWM [11] is also easily adapted to multilevel converter modulation by phase shifting the carriers. Although it appears more promising in theory, in practice as the number of converters increases, the variation between the analog generated carriers makes it increasingly difficult to achieve good carrier cancellation.

A digital implementation [12] is preferred for multilevel modulation. Switching edges with high accuracy and more importantly repeatability are needed to give the best carrier cancellation in a multilevel converter. Digital control is more easily modularized and is more noise immune.

As shown in Fig. 2(a and b), a software based multiple-sampled phase shifted carried based PWM is used for PWM control. This PWM method allows using high sampling control rates at low switching frequency. It can be considered as an extension either from a naturally sampled carrier based PWM or a uniform carried based PWM, which builds a connection between these two, therefore it has the benefits of both analog and digital implementations.

2.3. Current control

Current controller design is very critical for the current-controlled voltage source inverter system, especially for non-sinusoidal low switching frequency application such as medium voltage active power filter design. Existing current control techniques [13] can be classified into two main groups, linear and non-linear controllers. Non-linear controller is not suitable for low switching frequency applications and will not be discussed here.

In the linear group, there are four controllers that are generally studied for active filtering application: P stationary, PI stationary, PI synchronous and predictive (deadbeat) with constant switching frequency. As shown in Fig. 3, these conventional

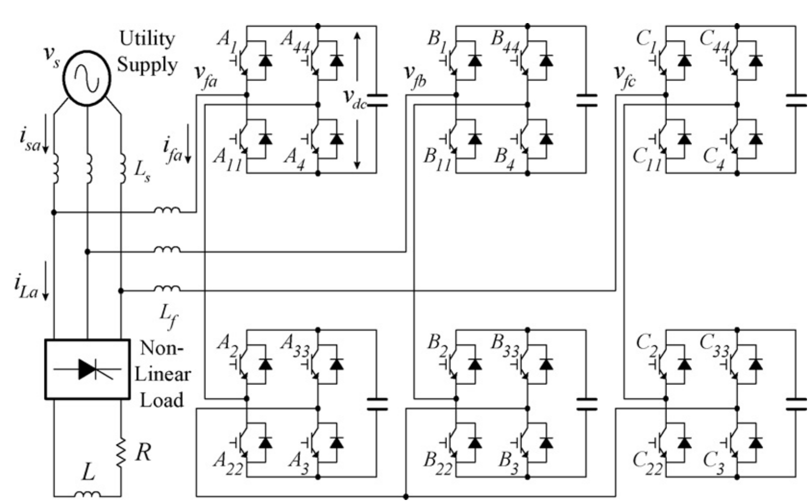

Fig. 1. The topology of proposed medium voltage multilevel inverter based active power filter. V_s (line-line) = 4160 V, R = 26 Ω, L = 0.15 H, L_s = 0.002–0.004 H (5–10% per unit), L_f = 0.002 H (5% per unit), C = 1000 μF, V_{dc}^* = 1875 V.