Comparison of Current Controllers for a Five-level Cascaded H-Bridge Multilevel Inverter

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Abstract:
The hysteresis current controller provides excellent dynamic performance, whereas the Proportional-Integral controller provides instantaneous current control and wave shaping, fixed inverter switching frequency resulting in only known harmonics. A comparative study between Hysteresis current control and Proportional-Integral (PI) current control using sinusoidal pulse width modulation (SPWM) techniques for a five-level cascaded H-bridge multilevel inverter is presented in this paper. A comparison has been made in terms of total harmonic distortion (THD) level at the three phase load current. The simulation study has been carried out with the help of *MATLAB Simulink* software and the performance of such controllers has been observed during load variations.

Keywords: Cascaded H-Bridge, Current controller, Hysteresis controller, Multilevel inverter, PI controller, Sinusoidal pulse width modulation (SPWM), Total harmonic distortion (THD)

1. Introduction

Presently, large electric drives and utility applications require advanced power electronics converters to meet the high power demands. As a result, multilevel inverter technology is a very efficient alternative for medium-voltage and high-power applications because of its fruitful advantages [1-4]. It can realize high voltage and high power output by using semiconductor switches without the use of transformer and dynamic voltage balance circuits. When the number of output levels increases, the harmonic content in the output voltage and current as well as electromagnetic interference decreases. The basic concept of a multilevel inverter is to achieve high power by using a series of power semiconductor switches with several lower dc voltage sources to perform the power conversion by synthesizing a staircase voltage waveform [4]. To obtain a low distortion output voltage nearly sinusoidal, a triggering signal should be generated to control the switching frequency of each power semiconductor switch. In the proposed study the triggering signals to multi level inverter (MLI) are designed by using the Sinusoidal Pulse Width Modulation (SPWM) technique.

The well-established topologies of multilevel inverters include neutral point clamped (NPC), flying capacitor and Cascaded H-bridge (CHB). These inverters have several advantages over the traditional inverters. The CHB inverter configuration has recently become very popular in high-power AC supplies and adjustable-speed drive applications. The CHB multilevel inverter is designed with a series of H-bridge (single-phase full bridge) inverter units in each of its three phases. The main focus of this paper is on the CHB inverter with different current control techniques including PI current control and hysteresis current control. These current control techniques are studied and compared with each other for analyzing their advantages and disadvantages. The current control techniques are also analyzed and compared based on current tracking, output quality, Total Harmonic distortion (THD), Modulation index and Load variations. To show the performance of the proposed CHB inverter, the *MATLAB*-simulink is used to simulate the five-level CHB inverter with the proposed current control techniques. The design and simulation of the five-level CHB inverter with predictive current control has to be introduced as a future work of this paper.

2. Inverter Model

The cascaded H-bridge multilevel inverter model is based on the series connection of H-bridges with separate dc sources. Since the output terminals of the H-bridges are connected in series, the dc sources must be isolated from each other (Fig.1). Owing to this property, CHB-MLIs have also been proposed to be used with fuel cells or photovoltaic arrays in order to achieve higher levels [1,5-7]. The resulting ac output voltage is synthesized by the addition of the voltages generated by different H-bridge cells. Each single phase H-bridge generates three voltage levels as +Vdc, 0, -Vdc by connecting the dc source to the ac output by different combinations of four switches (S_{11} , S_{12} ,S_{13} and S_{14}).

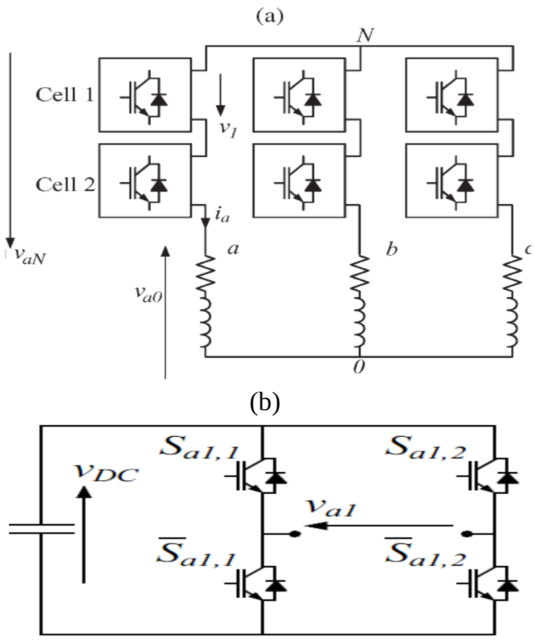


Figure1. CHB inverter. (a) Two-cell CHB three-phase inverter with *RL* load. (b) Topology of one cell

For each phase, the number of possible voltage levels is

$$L = 2C + 1 \quad (1)$$

where L is the number of levels and C is the number of series connected cells in one leg. In a three-phase inverter, the number of voltage level combinations K_L is

$$K_L = L^3 \quad (2)$$

On the other hand, each cell has two switching signals, and for C cells in each leg, the voltage of a leg of the inverter in terms of binary switching signals is

$$VaN = VDC \sum_{j=1}^{c}(Si\,j,1 - Si\,j,2) \quad (3)$$

where $S_{i\,j,1}$ and $S_{i\,j,2}$ are the switching signals of the phase i and cell j. The possible switching combination KS for a CHB inverter with C cells in each leg is

$$KS = 2^{6C} \quad (4)$$

In Fig. 1, the differential equation of the current of one leg (a) for a three-phase RL load connected to the inverter is

$$van(t) = L\frac{d\,ia(t)}{dt} + Ria(t) \quad (5)$$

where van is the voltage across the load in reference to its neutral point. However, the voltage across the load in terms of the inverter voltage is

$$v_{a0} = v_{aN} + v_{N0} \quad (6)$$

where $vN0$ is the *common-mode* voltage (vcm), defined as

$$Vno = Vcm = \frac{VaN + VbN + VcN}{3} \quad (7)$$

The load model can be expressed also as a vector equation using the following vectorial transformation:

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{\sqrt{3}}{3} & -\frac{\sqrt{3}}{3} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (8)$$

where a, b, and c are the three-phase variables of voltage or current, and α and β are the vectorial variables. Using this transformation, (5) can be described in terms of the vectorial variables $\alpha-\beta$ as

$$\mathbf{v}_{\alpha\beta}(t) = L\frac{d\mathbf{i}_{\alpha\beta}(t)}{dt} + R\mathbf{i}_{\alpha\beta}(t), \quad (9)$$

where $\mathbf{v}\alpha,\beta$ is the inverter voltage vector and $\mathbf{i}\alpha,\beta$ is the load current vector.

3. Modulation Techniques For CHB Inverter

There are different modulation techniques available for a CHB multilevel inverter [8-10]. Among all those techniques, PWM technique which produces less total harmonic distortion (THD) values is most preferable. Phase Shifted PWM (PS-PWM) and Level-shifted PWM (LS-PWM) are the natural extension of traditional PWM techniques. For generating triggering pulses to MLI, pure sinusoidal wave as modulating signal and multi carrier signal which is of triangular in shape have been considered [11]. For an L-level CHB inverter, (L-1) carrier signals are required.

In PSPWM, a phase shift is introduced between the carrier signals of contiguous cells, producing a phase-shifted switching pattern between them. When connected together, a stepped multilevel waveform is originated. It has been demonstrated that the lowest distortion can be achieved when the phase shifts between carriers are 180°/C (where C is the number of power cells) (Fig.2). The phase-shifts of the carriers produce multiplicative effect, which means that the total output voltage has a switching pattern with C times the frequency of the switching pattern of each cell. Hence, better total harmonic distortion (THD) is obtained at the output, using C times lower frequency carriers.

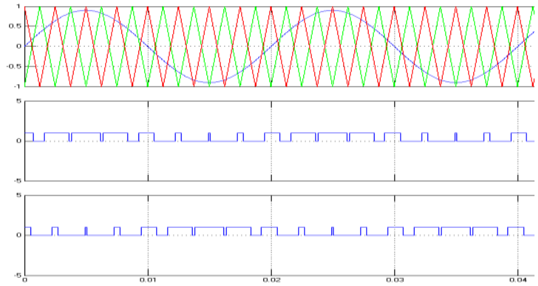


Figure 2. Phase Shifted PWM (PS-PWM)

In Level-shifted PWM (LS-PWM), the L-1 carriers are arranged in vertical shifts instead of the phase-shift used in PS-PWM. The carriers span the whole amplitude range that can be generated by the inverter.

They can be arranged in vertical shifts, with all the signals in phase with each other, called phase disposition (PD-PWM); with all the positive carriers in phase with each other and in opposite phase of the negative carriers, known as phase opposition disposition (POD-PWM); and alternate phase opposition disposition (APOD-PWM), which is obtained by alternating the phase between adjacent carriers [12]. An example of the phase disposition (PD-PWM) for the five-level CHB inverter (thus four carriers) is given in Fig. 3.

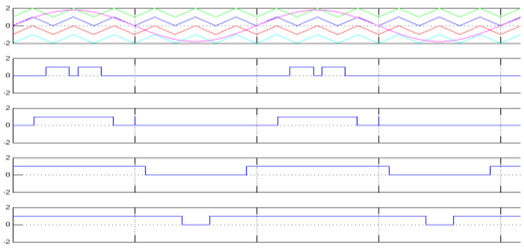


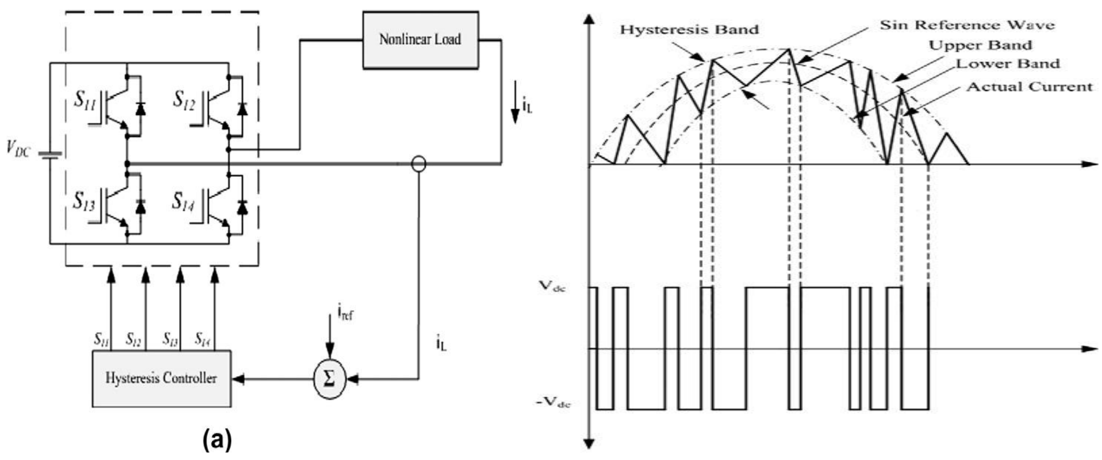
Figure 3. Phase disposition (PD-PWM)

4. Analysis of Current Controllers

4.1. Hysteresis current controller

The hysteresis modulation for power electronic converters is attractive in many different applications because of its unmatched dynamic response and wide command-tracking bandwidth. The hysteresis modulation is a feedback current control method where the load current tracks the reference current within a hysteresis band in nonlinear load application of CHB multilevel inverter. The block diagram of a hysteresis control of an H-bridge is shown in Fig.4a and the operation principle of the hysteresis modulation in Fig.4b. The controller generates the sinusoidal reference current of desired magnitude and frequency that is compared with the actual line current. If the current exceeds the upper limit of the hysteresis band, the next higher voltage level should be selected to attempt to force the current error towards zero. However, the new inverter voltage level may not be sufficient to return the current error to zero and inverter should switch to next higher voltage level until the correct voltage level is selected. As a result, the current gets back into the hysteresis band, and the actual current is forced to track the reference current within the hysteresis band. Three hysteresis controllers which are used to implement the correct voltage level selection are defined as double offset band three level, double band three level, and time-based three level hysteresis controllers [13, 14].

The switching frequency changes according to variations of the load parameters and operating conditions. This is one of the major drawbacks [15] of hysteresis control, since variable switching frequency can cause resonance problems. In addition, the switching losses restrict the application of hysteresis control to lower power levels.



(b)

Figure 4. Hysteresis current control: (a) block diagram of an H-bridge cell with hysteresis controller, (b) hysteresis current band and voltage curves of load feedback

4.2. Proportional-Integral Current Controller Using PWM

The PI current controller with PWM control scheme is shown in Fig.5. The error between the reference and the measured load current is processed by the PI controller to generate the reference voltages. A modulator is needed to generate the drive signals for the inverter switches. The reference load voltages are compared with a triangular carrier signal, and the output of each comparator is used to drive the CHB multilevel inverter.

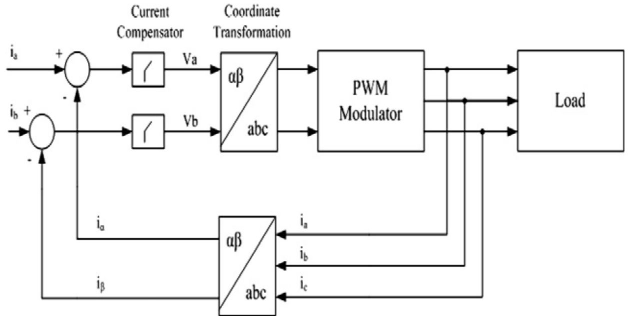


Fig. 5. The block diagram of PI current controller.

5. Simulation Results

Simulations of the CHB inverter were carried out using *Matlab*/*Simulink*. The load used for simulation results is an *RL* load. The input dc voltage, *V*DC = 100 V is considered for each cell.

Table.1. Simulation parameters

Parameters	Values
Input voltage(Vdc)	100 V
Load resistance(R)	47 Ω
Load inductance(L)	15 mH
Hysteresis Band Width(δ)	±0.1
Carrier Frequency(PI controller)	2.5KHz
Reference current	4A

The simulation parameters are given in table 1. The comparison of the PI current control with the Hysteresis current control is done by Current THD with variations in load.

The harmonic spectrum of load current waveform is analyzed using the Fast Fourier transform (FFT) and measured the THD of load current for different values of RL. Fig. 6.(a) shows the load voltage waveform and load current waveform for the hysteresis current controller and Fig. 6.(b) shows the reference current waveform for hysteresis controller. Fig.7.(a) shows the load voltage waveform and load current waveform for the PI controller. Fig.7(b) shows the reference current waveform for hysteresis controller. Fig.8(a-d) shows the harmonic spectrum of load current for the hysteresis current controller and Fig.9.(a-d) shows the harmonic spectrum of load current for the PI controller, respectively.

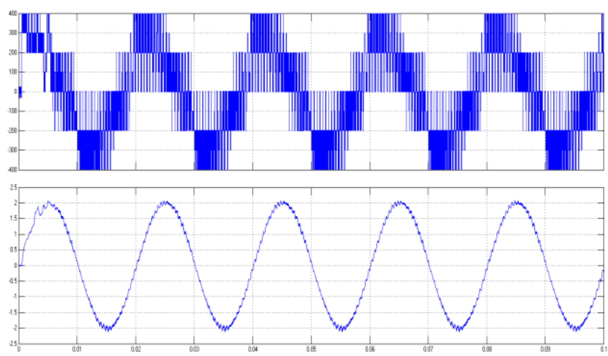


Figure 6(a). Load voltage and current waveform for hysteresis controller

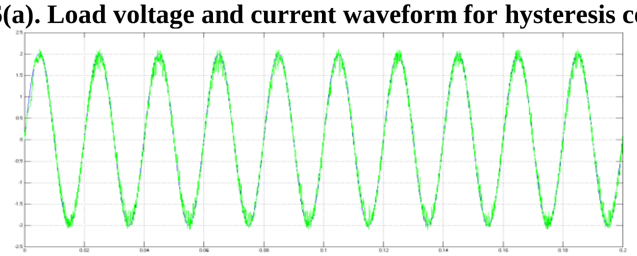


Figure 6(b). Reference current waveform for Hysteresis controller

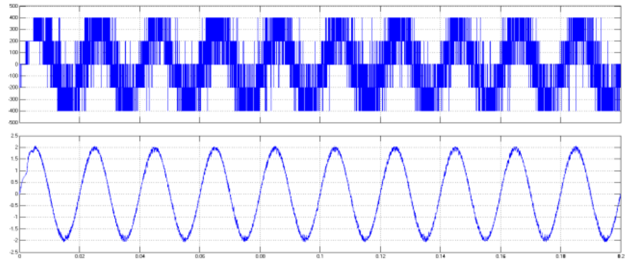


Figure 7(a). Load voltage and current waveform for PI controller

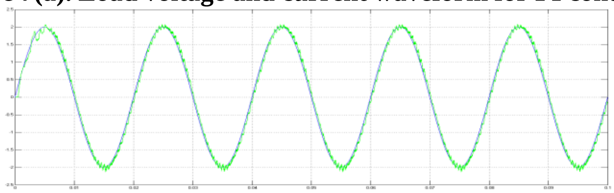


Figure 7(b). Reference current waveform for hysteresis controller

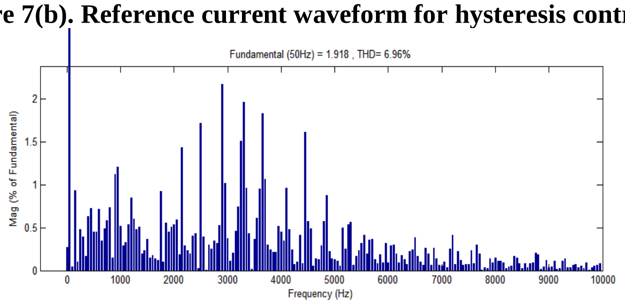


Figure 8(a). Harmonic spectrum for hysteresis controller (R=96Ω,L=35mH)

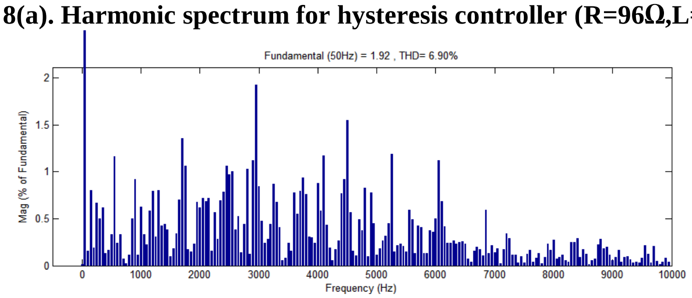


Figure 8(b). Harmonic spectrum for hysteresis controller (R=96Ω,L=30mH)

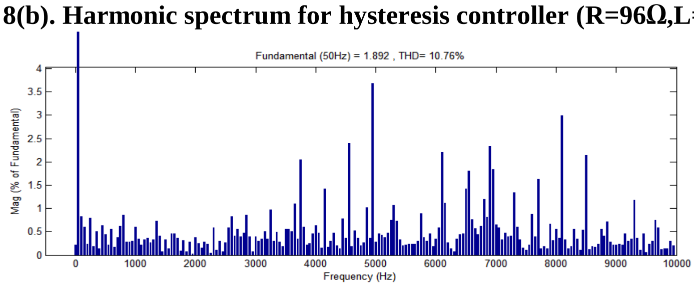


Figure 8(c). Harmonic spectrum for hysteresis controller (R=47Ω,L=15mH)

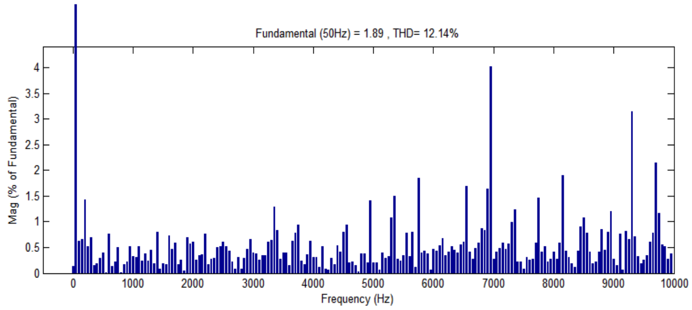


Figure 8(d). Harmonic spectrum for hysteresis controller (R=47Ω,L=10mH)

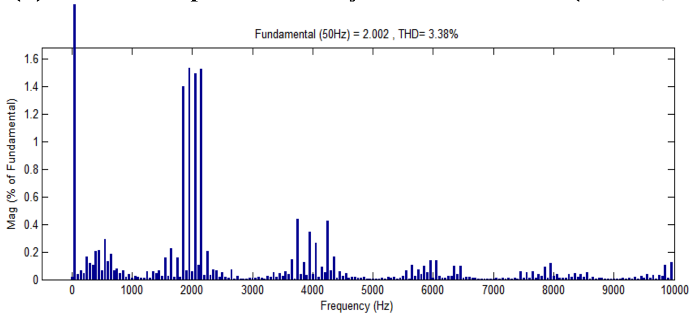


Figure 9(a). Harmonic spectrum for PI controller(R=96Ω,L=35mH)

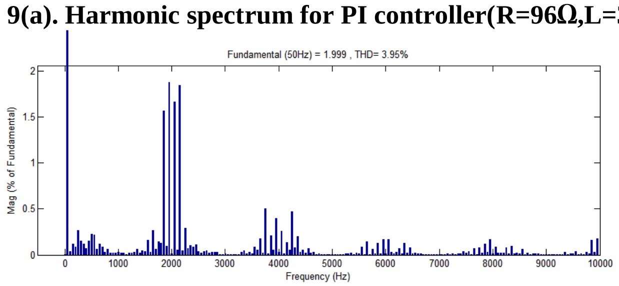


Figure 9(b). Harmonic spectrum for PI controller(R=96Ω,L=30mH)

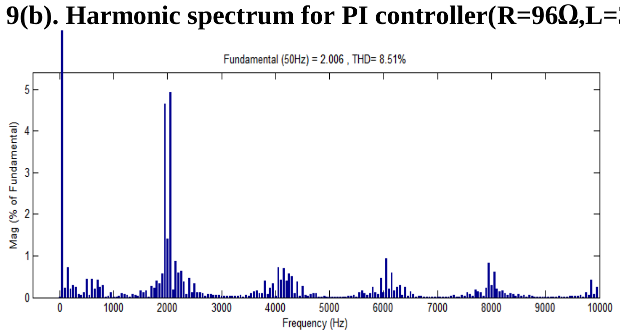


Figure 9(c). Harmonic spectrum for PI controller(R=47Ω,L=15mH)

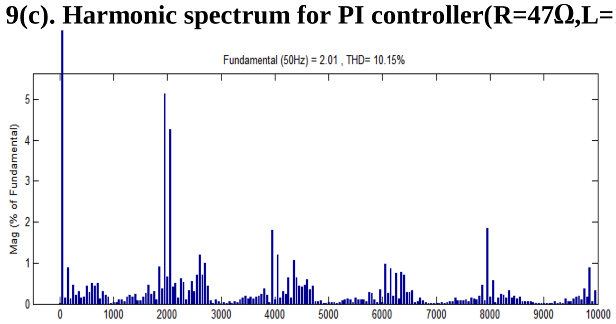


Figure 9 (d). Harmonic spectrum for PI controller(R=47Ω,L=10mH)

Table 2. Comparison of parameters for hysteresis and PI current controller

Different Loads	PI Current Controller	Hysteresis Current Controller
R=96Ω ,L=35mH	THD=3.38%	THD=6.96%
R=96Ω ,L=30mH	THD=3.95%	THD=6.90%
R=47Ω ,L=15mH	THD=8.51%	THD=10.76%
R=47Ω ,L=10mH	THD=10.15%	THD=12.14%

The different load parameters were tested and observed for the comparison of the performance of the hysteresis control and PI control with PWM techniques. The comparison results are shown in the table 2. As the load value increases, the THD value also increases but the PI current controller shows better response compared to the Hysteresis Controller. From fig.8 (a-d), it can be observed that the hysteresis control produces continuous and wide frequency range output current spectrum, which is considered as a disadvantage of this method. From fig. 9 (a-d), it is observed that the harmonic content generated when using the PI current control, is concentrated around the carrier frequency. This is considered as an advantage of the PI current control over the hysteresis control.

6. Conclusion

The CHB multilevel inverter's current has been controlled by the Hysteresis and Proportional - Integral (PI) current controllers. Hysteresis controller shows good dynamic response but with some noticeable disturbances in voltage and current waveforms. The PI current controller with PWM modulation technique shows slower response due to the dynamics of the closed current loops, but performed better compared to the hysteresis current controller. The harmonic spectrums for the two control methods were compared and the simulation results show that the current spectrum obtained with PI current control is better than the hysteresis current controller.

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