Journal of Novel Applied Sciences
Available online at www.jnasci.org
©2013 JNAS Journal-2013-2-10/443-448
ISSN 2322-5149 ©2013 JNAS

Assessment of Five-Level Cascade Voltage Source Inverter Harmonics Using Two SPWM and SHEM Switching Method

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ABSTRACT: Due to using of inverters in different application such as solar photovoltaic (PV), electric vehicles (EV), harmonic issue in power systems is very important, therefore, different switching methods have been presented for inverters in order to decrease harmonics. The main purpose of this paper is to assess harmonic situation in five-level cascade voltage source inverters (FCL-VSI) using two switching methods, selective harmonic elimination modulation (SHEM) and sinusoidal pulse width modulation (SPWM). To do so, a sample single phase FCL-VSI has been investigated by SHEM and SPWM switching methods and for each method, relation between modulation index and total harmonic distortion (THD) of output voltage has been obtained and also the effect of this parameter on the harmonic content has been studied. In order to obtain favourable results, two switching methods have been implemented on a sample inverter in MATLAB software and results have been evaluated.

Keywords: Five-Level Cascade Voltage Source Inverter (FCL-VSI), Selective Harmonic Elimination Modulation (SHEM), Sinusoidal Pulse Width Modulation (SPWM), Modulation Index, and Total Harmonic Distortion (THD)

INTRODUCTION

Different applications of inverters have begun to require higher power apparatus in recent years which some of them are related to their topologies variations and some are about their switching methods. Regarding limitations and problems of conventional inverters and also new energy sources such as PV, wind and fuel cell that can be connected to network using multilevel inverters (Rodriguez et al., 2002; Tolbert et al., 1999; Lai and Peng, 1996), multilevel inverters have been presented since 1975 (Baker and Bannister, 1975) At first, 3-level inverters (Nabae et al., 1981) and then multilevel inverters have been presented. Although the primary purpose of these multilevel inverters was to obtain high power due to parallel and series of switches, then it was shown that these inverters could improve harmonic situation. The most common multi level inverter (MLI) topologies classified into three types are diode clamped MLI (DC-MLI), flying capacitor MLI (FC-MLI), and cascaded H-Bridge MLI (CHB-MLI). The hybrid and asymmetric hybrid inverter topologies have been developed according to the combination of existing MLI topologies or applying different DC bus levels respectively (Williams 1992; Mohan et al., 1995; Bose, 2001; Rashid, 2001; Rodriguez et al., 2003; Su, 2005; Rodriguez et al., 2002).

Many different PWM pattern strategies have been reported in the literature for VSI. These include many different on-line (e.g., sinusoidal pulse width modulation, SPWM) or off-line (e.g., selective harmonic elimination and magnitude modulation, PWM-SHEM) patterns for fundamental magnitude control and harmonic reduction (Patel and Hoft, 1973; Murphy and Egan, 1983).To eliminate a number of harmonics selectively, an approach can be applied to VSI keeping in mind the above mentioned constraints (Espelage and Nowak, 1988; Namuduri and Sen, 1986). However, when the number of harmonics increases, such techniques fail to provide an acceptable solution. For example, a PWM-SHEM where fundamental magnitude is controlled besides eliminating the 5th, 7th, 11th, and 13th harmonics can be achieved simultaneously by the proposed techniques in the literature. But this technique cannot be achieved for multilevel voltage source inverters in literature.

In this paper, for a cascade FCL-VSI, harmonic situation has been investigated using two switching methods SHEM and SPWM. To do so, a sample inverter using two mentioned methods has been simulated in MATLAB and the relation between modulation index and total harmonic distortion (THD) has been determined. Total structure of this paper is organized as follow: first of all SPWM switching method and generating control signals are presented. Next, the relation between *m* and THD is determined. Then, SHEM switching method along with control signals are presented. Finally, the conclusion drawn from the study is provided.

FCL-VSI Using SPWM Switching Method

The structure of a FCL-VSI is shown in Figure 1. Among three topology of multi-level inverters DC-MLI, FC-MLI and CHB-MLI the last topology needs the least components in order to obtain higher levels. The mentioned inverter is composed of two 3-level conventional inverter and their outputs are cascaded together. Therefore, different PWM method can be used for switching of these inverters (Kincic et al., 2001; Chiasson et al., 2003; Nandhakumar and Jeevananthan, 2007; Leon et al., 2008; Lopez et al., 2008) that SPWM switching method is completely studied in this part.

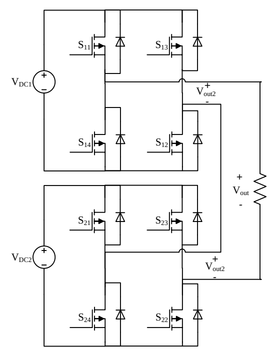

Figure 1. Five-level cascade voltage source inverter

In Figure1, pairs of switches (S_{11}, S_{14}), (S_{12}, S_{13}), (S_{21}, S_{24}) and (S_{22}, S_{23}) are conducted complementary. Switching signal, reference and triangular carrier signals are depicted in Figure 2. According to this figure, four triangular carrier signals are used that in comparing with sinusoidal reference waveform, the switching signals are extracted. It should be mentioned that if reference signal amplitude is less than the output of the second stage 3-level inverter will be equal to zero and total output will be close to first stage 3-level inverter output.

Output voltage waveform for each level and total output are shown in Figure 3. According to this figure, voltage waveform of each stage of inverter has three level but total output voltage has five level. According to this figure, it can be viewed that as level increasing from 3 to 5, waveform becomes more sinusoidal but it still has harmonic.

Carrier signal and reference signal frequency is considered as 1050 Hz and 50 Hz respectively. Hence, the first voltage harmonic in the output has 1000 Hz harmonic (20th harmonic order). It should be taken into account that although by increasing carrier signal frequency, the first harmonic frequency can be shifted to higher frequency; this increase leads to switches losses which is limitation for switches. According to Figure 3, as modulation index varies, fundamental component value of output voltage will be changed. As a result, modulation index variation changes the output notch width created in the output voltage which causes THD increase in output voltage.

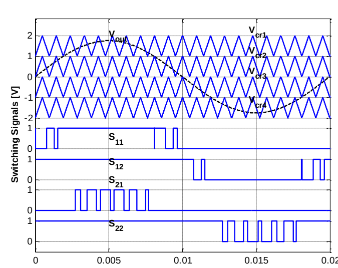

Figure 2. Reference, carrier and switching signals of FLC-VSI

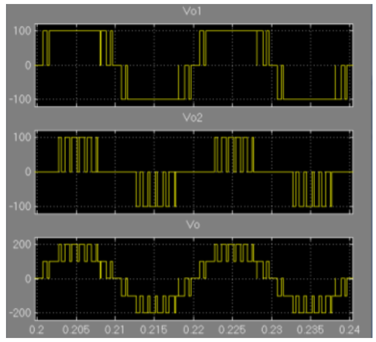

Figure 3. Waveforms of each stage and total Output voltages

For a specific output frequency, modulation index can be varied and then its effect on THD can be obtained. The impact of modulation index on the fundamental component amplitude is shown in Figure 4.

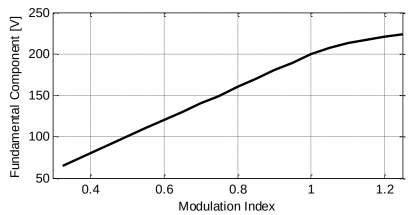

Figure 4. Relation between modulation index and fundamental component of output voltage

As it is illustrated in this figure, by increasing modulation index, fundamental component of output voltage is increases as it was expected before. But by increasing modulation index, based on Figure 5, output voltage THD is decreased. So, it is better that inverter works at a higher modulation index and if there is a need for higher output voltage, by increasing DC link voltages, output voltage value increases.

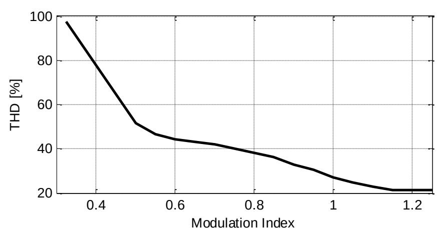

Figure 5. Relation between modulation index and THD of output voltage

FCL-VSI By SHEM Switching Method

One of the harmonic elimination methods in inverters is SHEM method. In this method, in order to eliminate *n* harmonics, *n* notches in quarter of output voltage should be created (Feshki, Habibinia et al. 6th June 2007; Sarabadani and Farahani 7-8 December 2009; Asadi, Borjlou et al. 2007; Farahani 2008; Farahani and Rashidi February 2010). If amplitude of fundamental component is also of concern, another notch should be created as well. So, by *n+ 1* notch in output waveform quarter, not only amplitude can be controlled but also n harmonics are eliminated. In (Sarabadani and Farahani, 2009) is shown that output current waveform in SHEM method only contains harmonic orders 6k±1, k=1, 2, 3… n.

In this method, lower order harmonics can be eliminated by suitable switching and higher harmonics orders can be removed from the output by high pass filter (which their size is quite small). In SHEM method, any number of harmonics from any order can be eliminated. In (Sarabadani and Farahani, 2009), SHEM method for single phase DC-MLI inverter has been completely presented.

In this section it is supposed that harmonics 5^{th}, 7^{th}, 11^{th} and 13^{th} should be eliminated along with fundamental component amplitude control, therefore 5 notches should be created in quarter of waveform which is shown in Figure 6. In this case, switching signal waveforms of pairs of switches (S_{12}, S_{11}), (S_{13}, S_{14}), (S_{22}, S_{21}) and (S_{23}, S_{24}) are similar.

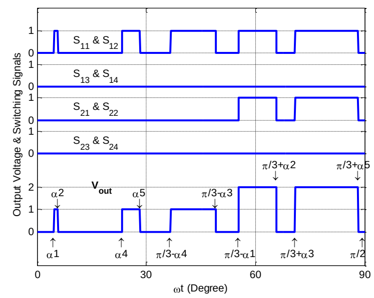

Figure 6. PWM-SHEM pattern for 5th, 7th, 11th, and 13th harmonics in the 0 - π/2 region

If Fourier series is written for output voltage in Figure 6, the relation of fundamental component voltage and harmonic component are written as (1) and (2) which are functions of α_1 to α_5 angels.

$$V_n = \frac{2V_{DC}}{n\pi}\Big[\cos n\alpha_1 - \cos n\alpha_2 + \cos n\alpha_4 - \cos n\alpha_5 + \cos n\left(\frac{\pi}{3}-\alpha_4\right) - \cos n\left(\frac{\pi}{3}-\alpha_3\right) + 2\cos n\left(\frac{\pi}{3}-\alpha_1\right) - 2\cos n\left(\frac{\pi}{3}+\alpha_2\right) + 2\cos n\left(\frac{\pi}{3}+\alpha_3\right) - 2\cos n\left(\frac{\pi}{3}+\alpha_5\right)\Big] \quad (1)$$

$$V_1 = \frac{2V_{DC}}{\pi}\Big[\cos\alpha_1 - \cos\alpha_2 + \cos\alpha_4 - \cos\alpha_5 + \cos\left(\frac{\pi}{3}-\alpha_4\right) - \cos\left(\frac{\pi}{3}-\alpha_3\right) + 2\cos\left(\frac{\pi}{3}-\alpha_1\right) - 2\cos\left(\frac{\pi}{3}+\alpha_2\right) + 2\cos\left(\frac{\pi}{3}+\alpha_3\right) - 2\cos\left(\frac{\pi}{3}+\alpha_5\right)\Big] \quad (2)$$

According to above equations, modulation index is defined as following equation:

$$m = \frac{V_1}{V_{DC}}, \qquad 0 \le m \le m_{max} \quad (3)$$

To eliminate harmonics 5th, 7th, 11th and 13th, harmonics components should be obtained from (1) and fundamental component should be determined from (2) and by these five nonlinear equations which have 5 variables (α_1 to α_5 angles), the values of these angels are obtained and then four harmonics are eliminated and fundamental component amplitude is controlled. The relation between modulation index and angels is specified in Figure 7 which is clear that for each *m* (output voltage), suitable angels can be selected.

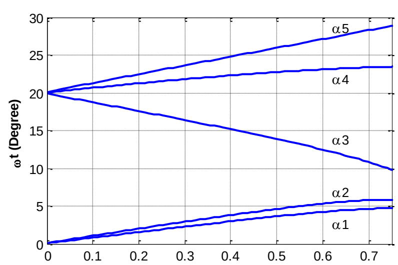

Figure 7. Chopping angles versus modulation index for Figure 6

For this switching method, fundamental component of output voltage and its THD versus different *m* values are obtained. For this purpose, first by using written code in MATLAB, switching signals of eight switches are generated and then for different *m* values, amplitude of fundamental component and THD values are calculated.

The relation between fundamental component and m is shown in Figure 8. According to this figure, as *m* increases from 0.4 to 1, output voltage value will be increased from 60v to 160v. The effect of *m* on THD value is illustrated in Figure 9. In this case, by decreasing *m* value from 1 to 0.4, THD value will be increased from 20% to 160% which is not favorable.

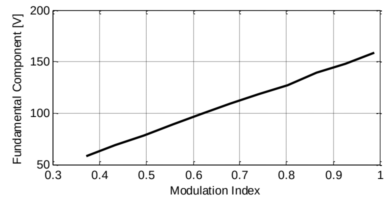

Figure 8. Relation between modulation index and fundamental component of output voltage in SHEM method

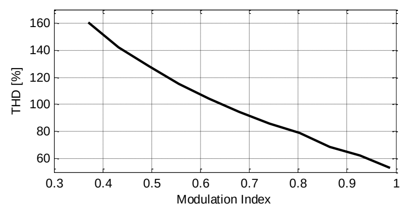

Figure 9. Relation between modulation index and THD of output voltage in SHEM method

Switching signals waveforms, output voltage of each stage and also total output voltage are plotted for a period in Figure 10 and Figure 11 respectively. This waveform does not contain harmonics 5^{th}, 7^{th}, 11^{th} and 13^{th} and the first harmonic is 17^{th} harmonic.

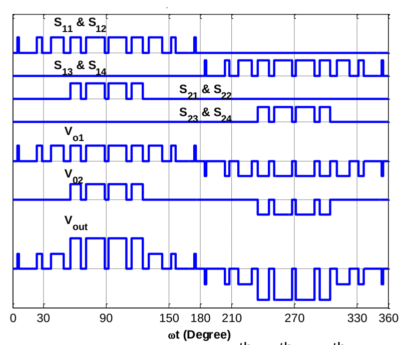

Figure 10. PWM-SHEM pattern for 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonics

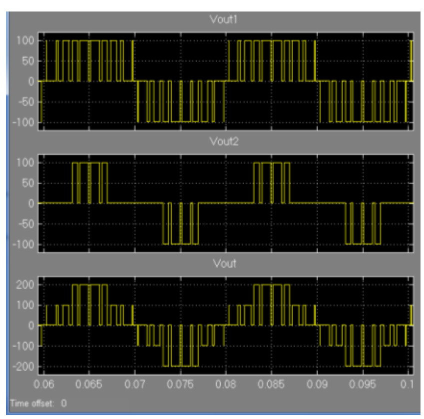

Figure 11. Waveforms of each stage and total Output voltages

CONCULSION

In this paper, harmonic situation of a FCL-VSI was investigated. For this purpose, first of all the structure of this inverter and then inverter harmonic situation were studied using two switching methods SPWM and SHEM. Besides, switching signals were obtained to access favorable output and each switching method was implemented on the inverter using MATLAB software. Moreover, the relation among *m* and fundamental component and THD were determined which were carried out by different simulations in MATLAB. It was shown that THD is a function of *m* that as *m* increases, THD value is decreased. Furthermore, it was specified that by increasing *m*, fundamental component will be increased as well. Output voltage of inverter can be varied by increasing DC-link voltage and also *m* variation. But it should be noted that because *m* variation can cause THD increase, as a result, to obtain different voltage in output, it is better that DC-link is increased along with *m* variation.

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