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FPGA Based Selective Harmonic Elimination Technique for Multilevel Inverter

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ABSTRACT

Harmonic elimination at the fundamental frequency is very much appropriate for high and medium range of power generation and applications. This paper considers a new technique for selective harmonic elimination (SHE), in which the total harmonic distortion (THD) is minimized when compared with that of the conventional one. With this technique, the harmonics at lower order are eliminated, which are more predominant than the higher ones. Cascaded H-Bridge inverter fed by a single DC is considered which is simulated with the switching angles generated by both the conventional method of SHE and the new method of SHE. The simulated results of the load voltage and the waveforms of the harmonic analysis are shown. The THD values are compared for the two techniques. The experimental results are also shown for the new technique. The switching angles are generated with the help of field programmable gated array (FPGA) in the hardware. The value of experimental THD of voltage is compared with that of simulated THD and the comparison prove that the results are satisfactory.

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1. INTRODUCTION

Multilevel inverters are very famous in applications employing high and medium power applications, because of their favourable characteristics like good quality output voltage and output current waveforms, less stress on the switches stress, and less EMI [1-4]. The main classification of multilevel inverter being the neutral point clamped inverter(diode clamped), cascaded H-bridge inverter, flying capacitor inverter [5] and the modular multilevel converters (MMCs) [6-8], [25 – 27]. There are many control techniques available for the multilevel inverter, the most popular and simple technique is the multi-carrier PWM technique. However, this technique is carried out with a high frequency carrier signal that increases the switching losses. Hence, the switching at the fundamental frequency is desired. Selective harmonic elimination(SHE) is the best PWM technique at the fundamental frequency, SHE produces the fundamental at the desired value by eliminating the dominant lower order harmonics [9-11]. In selective harmonic elimination technique, the angles for switching are found by solving non-linear transcendental equation set [12-13].

This paper proposes a SHE technique for the cascaded inverter which employs a single source of DC. The selective harmonic elimination technique further reduces the harmonic distortion of the voltage output of the multilevel inverter. The arrangement of the paper goes like this, Section 2 deals with the multilevel inverter employing single source of DC, Section 3 deals with selective harmonic elimination technique while section 4 brings out the new harmonic elimination, Section 5 brings out the simulation and experimental results and Section 6 concludes the paper.

2. MULTILEVEL INVERTER EMPLOYING SINGLE SOURCE OF DC

The cascaded Inverters are usually preferred to other configurations of the inverters as they do not require clamping diodes and capacitors. The only drawback of the cascaded inverter is that it uses separate DC sources. An m-level inverter uses $\left(\frac{m-1}{2}\right)$ DC sources, resulting in increased cost. The configuration proposed in this paper eliminates this disadvantage of the conventional cascaded multilevel inverter [14] [25 – 29].

The configuration requires only one DC source irrespective of levels, resulting in reduced cost. The proposed five-level cascaded inverter employing a single source of DC shown in Figure 1(a). The inverter uses only one DC source irrespective of the number of levels. An m-level inverter of the proposed inverter uses $\left(\frac{m-1}{2}\right)$ transformers. The output of the inverter is connected to the load through the transformers. The primary of the transformers are connected to the DC source through the bridges. The secondary transformer windings are connected in series aiding to the load [15-16].

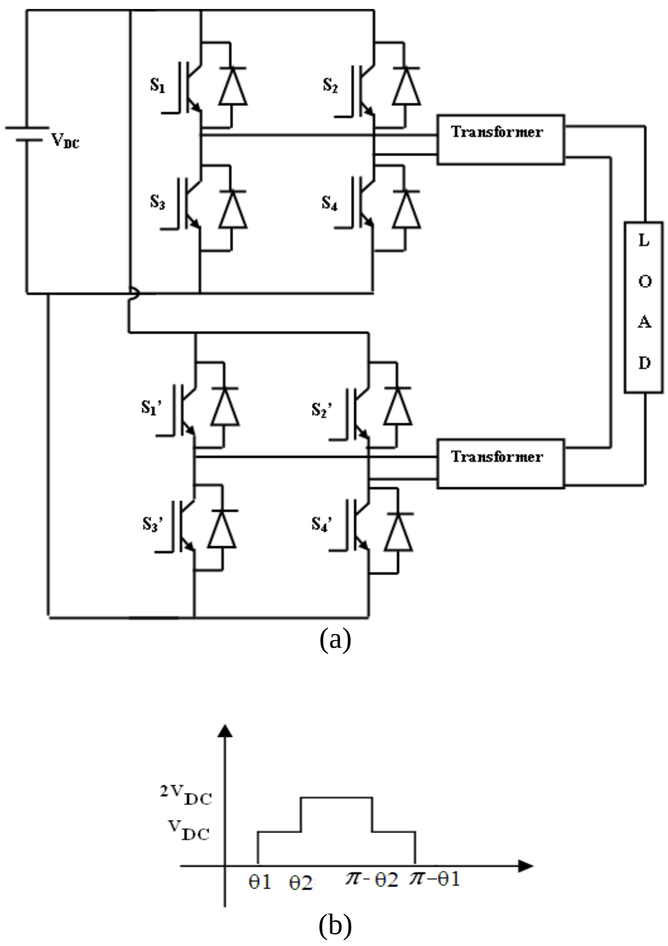


Figure 1. Five-level cascaded multilevel inverter with a single DC source (a) Circuit diagram (b) Waveform of voltage against the switching angles.

Modelling of five level inverter is done using the binary factors of each leg of the H bridges and are

$$H_{11} = \begin{cases} 0, S_1 = OFF, S_3 = ON \\ 1, S_1 = ON, S_3 = OFF \end{cases} \quad H_{21} = \begin{cases} 0, S_2 = OFF, S_4 = ON \\ 1, S_2 = ON, S_4 = OFF \end{cases}$$

$$H_{12} = \begin{cases} 0, S_1' = OFF, S_3' = ON \\ 1, S_1' = ON, S_3' = OFF \end{cases} \quad H_{22} = \begin{cases} 0, S_2' = OFF, S_4' = ON \\ 1, S_2' = ON, S_4' = OFF \end{cases}$$

Where, H_{11} and H_{21} are the binary states of the first and second leg of the first H Bridge respectively. H_{12} and H_{22} are the binary factors of the first and second leg of the second H Bridge respectively. Possible switching configurations of the CHB inverter are shown in the Table 1.

Table 1. Possible switching configurations of the CHB inverter

H11	H21	H12	H22	Vo
0	0	0	0	0
0	0	0	1	$-V_{DC}$
0	0	1	0	V_{DC}
0	0	1	1	0
0	1	0	0	$-V_{DC}$
0	1	0	1	$-2V_{DC}$
0	1	1	0	0
0	1	1	1	$-V_{DC}$
1	0	0	0	V_{DC}
1	0	0	1	0
1	0	1	0	$2V_{DC}$
1	0	1	1	V_{DC}
1	1	0	0	0
1	1	0	1	$-V_{DC}$
1	1	1	0	V_{DC}
1	1	1	1	0

3. SELECTIVE HARMONIC ELLIMINATION

Selective harmonic elimination (SHE) technique aims at switching ON and OFF the semiconductor switches in such a way that the desired value of voltage or current fundamental is obtained with less distortion. The angles for switching the devices at the fundamental frequency are calculated by solving the transcendental equation set that characterize the harmonics [17]. For a five-level inverter, two switching angles are to be generated by solving two equations. These equations are solved using the Newton-Raphson (N-R) method that solves the nonlinear equations with initial approximate values is the one among the fastest methods of iteration [18].

Figure 1(b) shows the waveform of voltage for the five-level inverter against the switching angles for a half cycle. Expressing this waveform in Eqn. (1) with the help of Fourier series.

$$v_a(\omega t) = \sum_{n=1,3,5}^{\infty} \frac{4V_{DC}}{n\pi} (\cos\theta_1 + \cos\theta_2) \sin(n\omega t) \quad (1)$$

θ_1 and θ_2 are the switching angles, where $0 < \theta_1 < \theta_2 < \pi/2$. From Equation 1, fundamental voltage is given by Equation 2 [19-21].

$$V_1 = \frac{4V_{DC}}{\pi} (\cos\theta_1 + \cos\theta_2) \quad (2)$$

The peak fundamental voltage is $V_{m1} = \frac{4V_{DC}}{\pi}$, i.e., it is the value of the fundamental voltage with all the switching angles equated to zero. Modulation index (M_I) is defined as the ratio between the voltage fundamental and the peak voltage fundamental, $M_I = \frac{V_1}{V_{m1}}$. For eliminating the desired harmonic, say the third harmonic, n=3 is substituted in Equation 1 and is equated to zero. The angles for the conventional SHE for a five-level inverter are calculated using the fundamental and the third harmonic equations given by Equations (3-4).

$$\cos\theta_1 + \cos\theta_2 = \frac{\pi V_1}{4V_{DC}} \tag{3}$$

$$\cos(3\theta_1) + \cos(3\theta_2) = 0 \tag{4}$$

Solving (3) and (4) by Newton-Raphson method, the angles are calculated as θ_1= 0.179 radians and θ_2=0.87 radians. Hence, the third harmonic is eliminated but the other harmonics like fifth, seventh, etc are present.

4. NEW HARMONIC ELLIMINATION

A new SHE technique to minimize the fifth harmonic, along with the elimination of the third order harmonic is considered in this paper. This is achieved by using the equation of fifth order harmonic along with equation of the third order harmonic and leaving the fundamental equation. Fifth harmonic is not completely eliminated but is reduced to a small value by equating the fifth harmonic equation to a minimum value, say 0.0001, as given by Equation 5.

$$\cos(5\theta_1) + \cos(5\theta_2) = 0.0001 \tag{5}$$

By solving Equations. (4 & 5) by N-R method [22], the θ_1 and θ_2 values are found to as θ_1= 0.2094 rad and θ_2= 0.8378 rad.

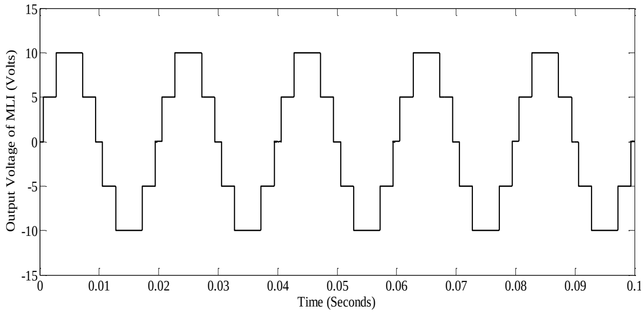
The new selective harmonic elimination reduces one more additional harmonic. For a five level inverter, the technique mitigates the fifth order harmonics in addition to the third order harmonics. For a seven-level inverter, the technique mitigates the seventh order harmonics alongwith the elimination of the third and fifth order harmonics and so on. Hence, the THD value is further reduced. The THD is one among the various performance parameters of inverter circuit and it can be found using Fourier series [23]. THD is the ratio between the sum of all the harmonic components and the fundamental component of the voltage or current.

5. RESULTS AND ANALYSIS

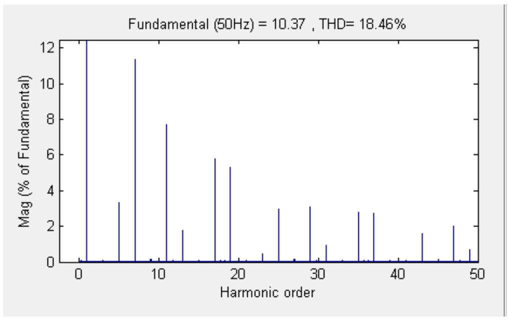
5.1. Simulation results

Simulation work of the five-level inverter is done using MATLAB/ Simulink with the conventional SHE and the new SHE techniques. Waveforms of the simulated output voltage, harmonic analysis and the PWM pattern for both the techniques are obtained.

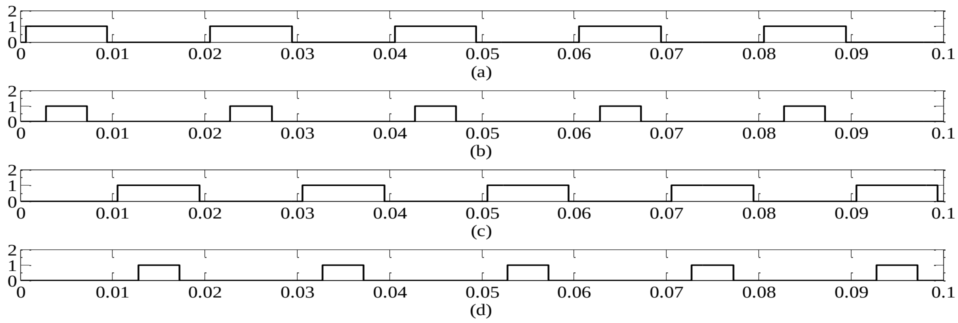
Figure 2(a-c) respectively shows the simulated output voltage of the MLI, the harmonic analysis and the PWM pattern for the conventional SHE. Figure 3(a- c) respectively shows the wave forms of output voltage of the MLI, harmonic analysis and PWM pattern for the new SHE. From the Figures. 2(b) and 3(b), it is evident that the THD value of the voltage output is 18.46 % with the conventional SHE technique while it is 17.4 % with the new SHE method. Hence, it is clear that the proposed SHE method results in the lesser value of voltage THD as compared to that of the conventional SHE method. The Table 2 compares the THDs of the voltages of the MLI for the two SHE techniques.



(a)

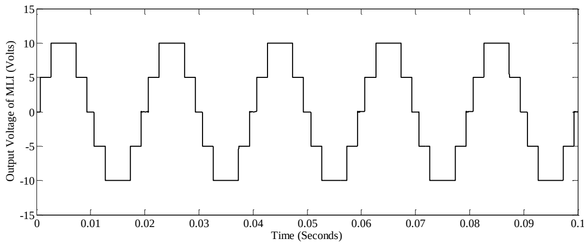


(b)

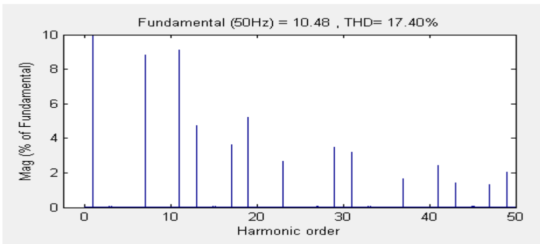


(c)

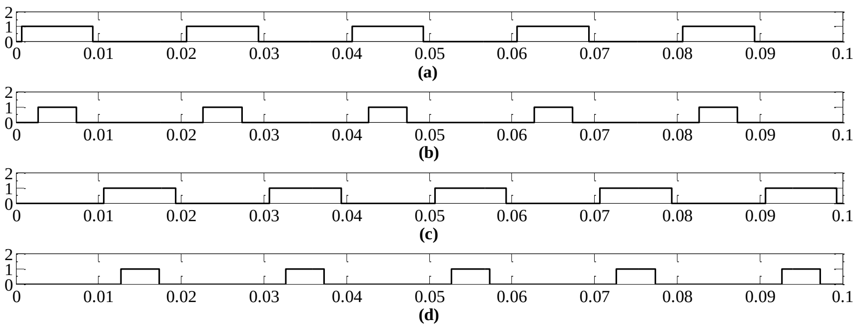
Figure 2. (a) Output voltage of the MLI, (b) Harmonic Analysis, and (c) PWM pattern for the conventional SHE.



(a)



(b)



(c)

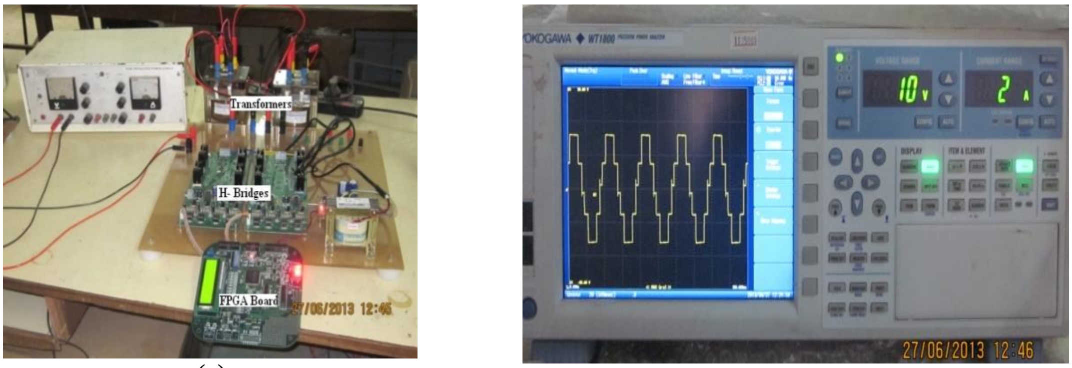
Figure 3. (a) Output voltage waveform of MLI, (b) waveform of Harmonic Analysis, (c) waveform of PWM Pattern for new SHE

Table 2. Voltage THD comparison

Voltage THD with the conventional SHE technique	Voltage THD with the new SHE technique
18.46%	17.40%

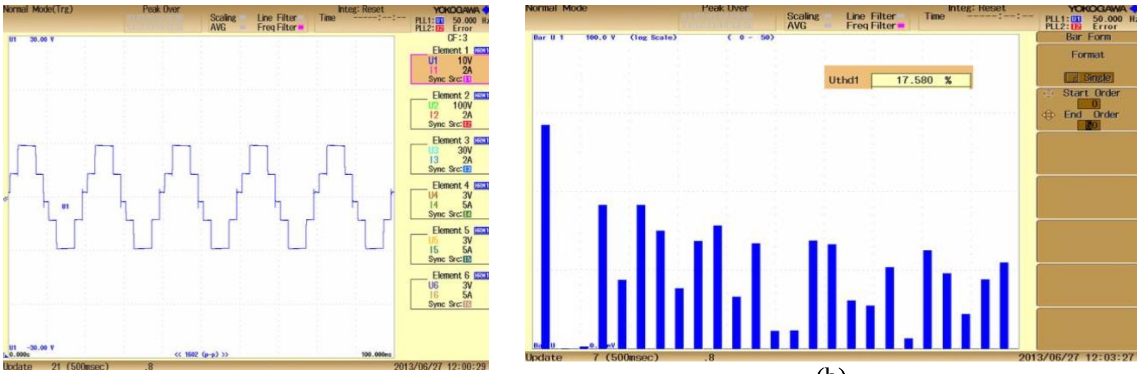
5.2. Experimental results

The proposed five-level CHB inverter is developed in hardware and is experimentally verified. In the hardware, MOSFET switches are used. The switches are fired with the switching angles obtained with the new SHE technique. The switching angles are produced with the FPGA SPARTAN 3E board. Spartan-3 FPGAs are perfectly suited to all type of electronics applications due to its low cost. FPGA realizes high speed switching and attains a high over sampling rate [24]. Figure 4(a) and 4(b) show the snapshot of hardware setup and the output voltage respectively.



(a) (b)

Figure 4. (a) Snapshot of the hardware setup, (b) Snapshot of the output voltage waveform



(a) (b)

Figur 5. (a) Output voltage, (b) Harmonic analysis.

It is seen from the Figure 5(b), that the third harmonic is removed and the fifth harmonic is reduced to a low value. It is also seen from the same figure that the voltage THD for experimental output voltage with new SHE is 17.58% considering the maximum of fifty harmonic order. Table 3 shows the comparison of voltage THDs

Table 3. Comparison of the Voltage THDs of the simulated and experimental values

Voltage THD with the new SHE technique for simulated voltage	Voltage THD with the new SHE technique for experimental voltage
17.40%	17.58%

6. CONCLUSION

A new SHE method is proposed and implemented for the five-level inverter. The new method has the advantage of eliminating one more harmonic when compared to the conventional one. Simulation has been carried out for the inverter with the conventional and the new SHE techniques. The simulated waveforms of output voltage, THD analysis and the PWM pattern are obtained. It is found from the simulated harmonic analysis waveform that the voltage THD is 18.46% for conventional SHE while it is 17.40% for the new SHE. Hence, the proposed SHE method has lesser THD value when compared to that of the conventional SHE method. The five level inverter with single source of DC is developed and verified with the new SHE experimentally. The experimental results of output voltage and harmonic analysis are obtained. The THD value for the new SHE is verified experimentally verified. The THD for the hardware output voltage is 17.58 %, which almost close to the simulated value.

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