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Optimal Selective Harmonic Elimination in Cascaded H-Bridge Inverters

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***Abstract* – Because of their straightforward construction and ease of implementation, cascaded structured multilevel inverters are rising in popularity. We present in this work the best selective harmonic elimination approach for a nine-level converter. We use this method to suppress the chosen lower order harmonic, which results in a significant reduction in the overall harmonic distortion of the inverter. The Newton-Rapson method is used to determine the switching angles that will result in the least amount of specific lower order harmonics. The harmonics that are deleted are in the following order: third, fifth, and seventh harmonics are eliminated. All of the simulation results for a nine-level inverter created using SIMULINK are given.**

***Index Terms* – Iterative methods ,Nine level MLI, Control of inverter, Modular Inverter, THD, optimum angles.**

I INTRODUCTION

Despite the fact that several topologies are being created in the field of power electronics, adequate power quality is still not being obtained. When using the MLI, it is important to have the lowest possible quality of output created at the load terminals. THD is typically extremely low when there are a high number of levels, however increasing the number of levels in an inverter is not feasible owing to the increased switching loss, increased number of components, and increased complexity of the circuits as the size of the inverter rises, for example. Whenever possible, it is recommended to produce high-quality output voltage with a small number of levels in an MLI. After an MLI has been configured with a certain number of levels, the control mechanism used to regulate that MLI's output voltage becomes the other factor that influences the output voltage's quality. In MLIs, these control approaches are referred to as modulation methods, which is short for modulation methods. There are many different kinds of modulation techniques accessible in the literature. The switching frequency of the major switches in MLIs is used to categorize these approaches, which are then further subdivided. The former are referred to as high frequency techniques, whereas the latter are referred to as fundamental frequency methods. High frequency techniques such as SPWM, space vector modulation, trapezoidal modulation, and so on are examples of high frequency methods, while fundamental frequency methods such as NLC, space vector control, and so on are examples of fundamental frequency methods. The major disadvantage of high frequency systems is the substantial switching loss that occurs as a result of the increased switching frequency. The basic frequency modulation approaches, on the other hand, suffer from less loss.

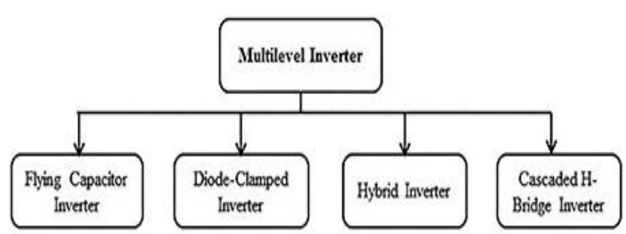

Figure 1: Classification of Multilevel Inverters.

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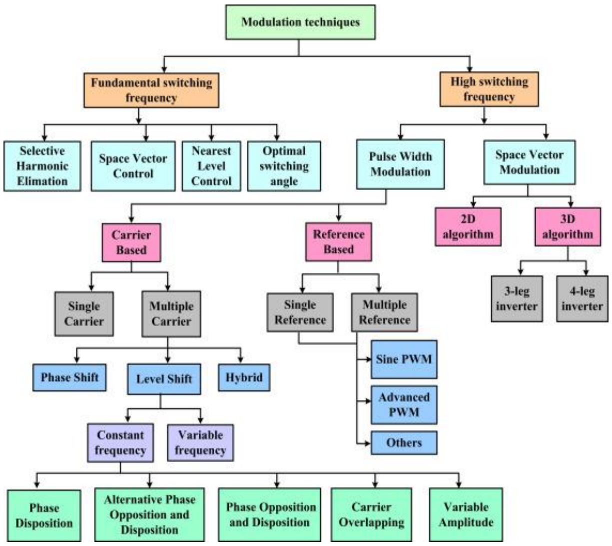

Figure 2: Classifications of Modulation Methods.

The many kinds of multilevel inverters and modulation techniques are shown in the preceding figures 1 and 2, respectively.

The goal of all modulation techniques, despite the fact that there are many different forms, is to reduce the total harmonic distortion (THD) of the voltage to the lowest feasible level. THD, on the other hand, is the total influence of individual harmonic components, which means it is a mixture of all of the harmonic components in a waveform, as opposed to a single harmonic component. It is possible to enhance the voltage quality and minimize the total harmonic distortion (THD) in a waveform by removing particular harmonic components that are large in size. However, the majority of modulation systems do not have control over the various harmonic components of the signal. It is necessary to use a particular procedure in order to minimize the chosen harmonic component from among all of the other harmonic components that are accessible.

The selective harmonic elimination or mitigation approach is the only method that has the capability of controlling all of the harmonics at the same time. With this procedure, it is feasible to decrease or attenuate the effects of any harmonic that is present in the waveform in question. This approach may be used to any inverter with any number of levels, regardless of the manufacturer. It is referred to as SHE or SHEPWM in the popular press.

It is shown in this study that the optimal SHE approach may be used with the CHB topology to design and analyze a nine-level inverter. Third order, fifth order, and seventh order harmonics are among the harmonics that have been removed.

II OPTIMUM SELECTIVE HARMONIC ELIMINATION

It is necessary to do the following procedures in order to determine the appropriate switching angles for reducing the associated harmonics from the voltage waveform using this method/technique. There are a number of stages involved in this process

- Problem formulation.
- Writing the final equations.
- Solving the non linear equations using some method.
- Generating the gate pulses according to the switching angles obtained.

A Problem Formulation

When it comes to putting together an issue, the very first step is to look at the nature of the output voltage waveform, which is shown in Figure 3 below. In this waveform, there is a lot of repetition of the quarter wave symmetry.

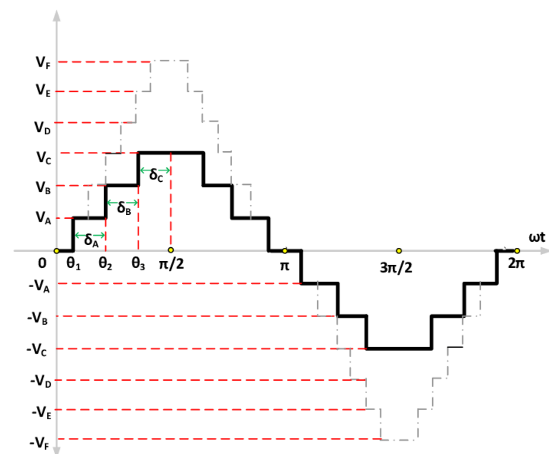

Figure 3: General output voltage waveform.

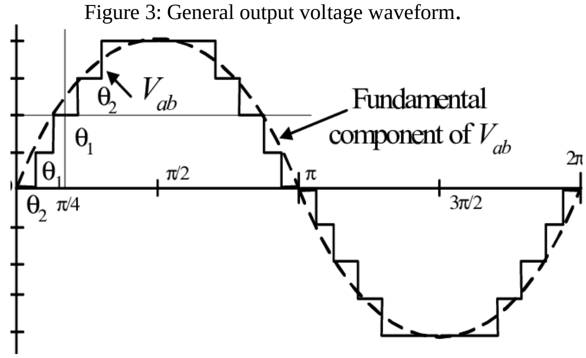

Figure 4: Nine level output waveform.

The switching angles are shown in the above

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illustration. The goal of this stage is to determine the values of those angles that will lessen the effects of the specified harmonics.

The H bridge circuit is illustrated in Figure 3. This has the capability of generating three levels in the output voltage waveform. Table 1, which is presented below, contains the switching tables that are used to create three different voltage levels.

The third, fifth, and seventh order harmonics are the ones that need to be eliminated in this task. Because a nine-level inverter is comprised of four bridges, there will be four switching angles in the first quarter cycle of operation. As a result, there are a maximum of four degrees of freedom. This implies that with those four degrees of freedom, a maximum of any four harmonics may be removed at the same time.

B Writing the Equations

Because the MLI is symmetrical, the magnitude of all of the voltage sources is the same. As a result, it is written as

$$V_1^* = V_2^* = V_3^* = V_4^* = V^* = \frac{V}{V_{dc}} \quad (1)$$

The following is the requirement that must be met in order to compute the switching angles:

$$0 < \alpha_k < \frac{\pi}{2}, \quad k = 1, 2, 3, 4 \quad (2)$$

$$\begin{cases} \cos(3\alpha_1) + \cos(3\alpha_2) + \cos(3\alpha_3) + \cos(3\alpha_4) = 0 \\ \cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) + \cos(5\alpha_4) = 0 \\ \cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) + \cos(7\alpha_4) = 0 \end{cases} \quad (3)$$

The first equation in the preceding formula (3) is for the third harmonic, the second equation is for the fifth harmonic, and the final equation is for the seventh harmonic.

The following formulas are obtained by simplifying the aforementioned equations..

$$\begin{cases} 2\cos\left(\frac{3}{2}(\alpha_1+\alpha_2)\right)\cos\left(\frac{3}{2}(\alpha_1-\alpha_2)\right) + \\ +2\cos\left(\frac{3}{2}(\alpha_3+\alpha_4)\right)\cos\left(\frac{3}{2}(\alpha_3-\alpha_4)\right) = 0 \\ 2\cos\left(\frac{5}{2}(\alpha_1+\alpha_2)\right)\cos\left(\frac{5}{2}(\alpha_1-\alpha_2)\right) + \\ +2\cos\left(\frac{5}{2}(\alpha_3+\alpha_4)\right)\cos\left(\frac{5}{2}(\alpha_3-\alpha_4)\right) = 0 \\ 2\cos\left(\frac{7}{2}(\alpha_1+\alpha_2)\right)\cos\left(\frac{7}{2}(\alpha_1-\alpha_2)\right) + \\ +2\cos\left(\frac{7}{2}(\alpha_3+\alpha_4)\right)\cos\left(\frac{7}{2}(\alpha_3-\alpha_4)\right) = 0 \end{cases} \quad (4)$$

As a result, the aforementioned equations will be transformed once again

$$\begin{cases} \alpha_1+\alpha_2 = \frac{\pi}{3} \\ \alpha_3+\alpha_4 = \frac{\pi}{3} \\ 2\cos\left(\frac{5\pi}{6}\right)\left[\cos\left(\frac{5}{2}(\alpha_1-\alpha_2)\right)+\cos\left(\frac{5}{2}(\alpha_3-\alpha_4)\right)\right] = 0 \\ 2\cos\left(\frac{7\pi}{6}\right)\left[\cos\left(\frac{7}{2}(\alpha_1-\alpha_2)\right)+\cos\left(\frac{7}{2}(\alpha_3-\alpha_4)\right)\right] = 0 \end{cases} \quad (5)$$

We may derive the following result by simplifying the previous equation even further

$$\begin{cases} \alpha_1+\alpha_2 = \frac{\pi}{3} \\ \alpha_3+\alpha_4 = \frac{\pi}{3} \\ 4\cos\left(\frac{5\pi}{6}\right)\cos\left(\frac{5}{2}\left(\frac{\alpha_1-\alpha_2+\alpha_3-\alpha_4}{2}\right)\right)\cdot \\ \cos\left(\frac{5}{2}\left(\frac{\alpha_1-\alpha_2-\alpha_3+\alpha_4}{2}\right)\right) = 0 \\ 4\cos\left(\frac{7\pi}{6}\right)\cos\left(\frac{7}{2}\left(\frac{\alpha_1-\alpha_2+\alpha_3-\alpha_4}{2}\right)\right)\cdot \\ \cos\left(\frac{7}{2}\left(\frac{\alpha_1-\alpha_2-\alpha_3+\alpha_4}{2}\right)\right) = 0 \end{cases} \quad (6)$$

$$\begin{cases} \alpha_1+\alpha_2 = \frac{\pi}{3} \\ \alpha_3+\alpha_4 = \frac{\pi}{3} \\ \alpha_1-\alpha_2+\alpha_3-\alpha_4 = \frac{2\pi}{5} \\ 4\cos\left(\frac{7\pi}{6}\right)\cos\left(\frac{7\pi}{10}\right)\cos\left(\frac{7}{2}\left(\frac{\alpha_1-\alpha_2-\alpha_3+\alpha_4}{2}\right)\right) = 0 \end{cases} \quad (7)$$

$$\begin{cases} \alpha_1+\alpha_2 = \frac{\pi}{3} \\ \alpha_3+\alpha_4 = \frac{\pi}{3} \\ \alpha_1-\alpha_2+\alpha_3-\alpha_4 = \frac{2\pi}{5} \\ \alpha_1-\alpha_2-\alpha_3+\alpha_4 = \frac{2\pi}{7} \end{cases} \quad (8)$$

The above (8) can be written in matrix form as

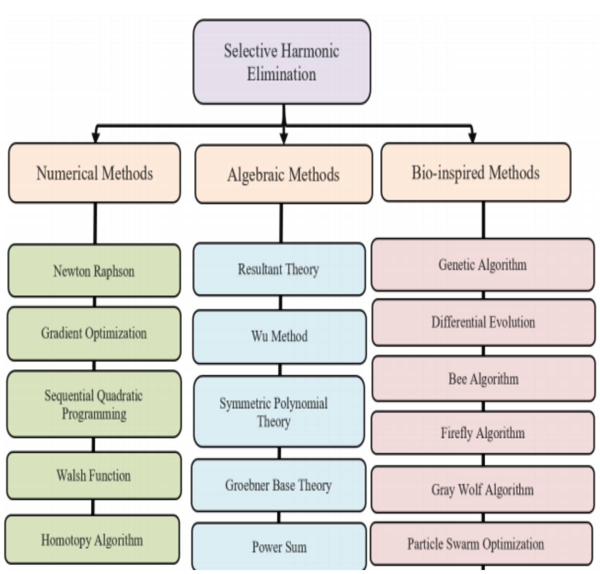
$$\begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix} \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{pmatrix} = \begin{pmatrix} \frac{\pi}{3} \\ \frac{\pi}{3} \\ \frac{2\pi}{5} \\ \frac{2\pi}{7} \end{pmatrix} \quad (9)$$

Angles may be calculated by resolving the expressions shown above. It is possible to utilize these angles as a starting point for determining the ideal switching angles that will result in the minimum of the specified harmonics.

C Solving the Equations

In order to solve the equations that were generated in the preceding part, a variety of techniques might be utilized. In their nature, all of the equations are nonlinear, and this leads in a variety of solutions. Following is a list of the many approaches that may be used to solve the nonlinear equation in the SHE method, which can be found in the Table below.

Table 1: Various methods for SHE.



When solving the nonlinear equations generated in the preceding part, the Newton Raphson technique is used, which is described in detail below. The switching angles are determined immediately from the Newton Raphson equation when it is applied. As shown in the following table II, the angle is calculated for different values of modulation index after the harmonic components mentioned before have been removed from the equation.

Table 2: Switching angles obtained by SHE.

m	Switching angles [rad]
0.3	$4.429 \cdot 10^{-1}$, 1.071, 1.490, 2.118
0.4	$3.417 \cdot 10^{-1}$, $9.700 \cdot 10^{-1}$, 1.389, 2.017
0.5	$2.360 \cdot 10^{-1}$, $8.644 \cdot 10^{-1}$, 1.283, 1.912
0.6	$1.239 \cdot 10^{-1}$, $7.522 \cdot 10^{-1}$, 1.171, 1.799
0.7	$2.193 \cdot 10^{-3}$, $6.305 \cdot 10^{-1}$, 1.049, 1.678
0.8	$1.347 \cdot 10^{-1}$, $4.936 \cdot 10^{-1}$, $9.125 \cdot 10^{-1}$, 1.541
0.9	$2.987 \cdot 10^{-1}$, $3.296 \cdot 10^{-1}$, $7.485 \cdot 10^{-1}$, 1.377
1	$9.648 \cdot 10^{-2}$, $5.154 \cdot 10^{-1}$, $5.318 \cdot 10^{-1}$, 1.144

The following table II lists the four switching angles that occur during the first quarter cycle in radian. Table II: Four Switching Angles During the First Quarter Cycle Through transformations, they may be readily turned into degrees of freedom.

III NINE LEVEL CHB MLI

This section describes the construction and functioning of a 9-level CHB MLI, as well as its components. In addition, the switching states are shown. The circuit architecture of the 9-level MLI is seen in Figure 5.

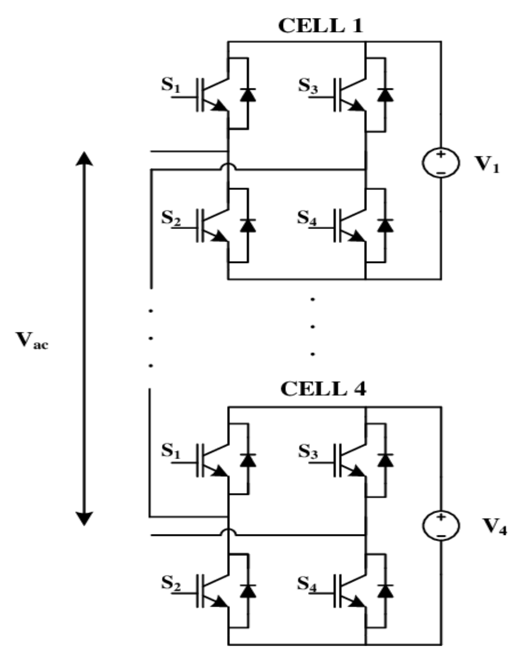


Figure 5: Nine level CHB MLI.

The MLI under consideration is comprised of four H-bridges. Each bridge is made up of four switches, which are connected together. Each bridge may produce three levels on its own, and the bridges together can generate a total of nine levels, four of which are positive, four of which are negative, and one of which is zero.

The magnitude of the DC voltage sources is the same as before. All four bridges are joined together in a cascaded configuration. The creation of different levels is controlled by a number of different switches. It has the ability to produce both positive and negative levels. There are a variety of solutions available for creating zero voltage levels..

Table 3: Switching states of switches.

Levels	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
0	ON	OFF	ON	OFF	ON	OFF	ON	OFF
V_{dc}	ON	ON	OFF	OFF	ON	OFF	ON	OFF
$2V_{dc}$	OFF	OFF	ON	ON	ON	ON	OFF	OFF
$3V_{dc}$	ON	OFF	ON	OFF	ON	ON	OFF	OFF
$4V_{dc}$	ON	ON	OFF	OFF	ON	ON	OFF	OFF
0	OFF	ON	OFF	ON	OFF	ON	OFF	ON
$-V_{dc}$	OFF	OFF	ON	ON	OFF	ON	OFF	ON
$-2V_{dc}$	ON	ON	OFF	OFF	OFF	OFF	ON	ON
$-3V_{dc}$	OFF	ON	OFF	ON	OFF	OFF	ON	ON
$-4V_{dc}$	OFF	OFF	ON	ON	OFF	OFF	ON	ON

The switching states of different switches are shown in Table III, which is displayed in the preceding illustration. There are a total of four switches that are turned on to produce every given level.

A THD Calculation

THD is the unit of measurement for power quality. As a result, it is critical to determine the total harmonic distortion (THD) of any waveform, and in particular the voltage waveform of an MLI.

Following is an equation that may be used to calculate the THD

$$\text{THD}\% = \frac{\sqrt{\sum_{n=3,5\ldots}^{49} H_n^2}}{H_1} 100$$

The harmonic order is represented by the letter H in the previous phrase. The fundamental, second order, and third order harmonic components are represented by the letters H1, H2, H3,..., respectively. The total harmonic distortion (THD) is given as a %, and all of the harmonics will be expressed as percentage values as well.

IV SIMULATION RESULTS

This section contains all of the simulation results that have been produced to yet. Simulink is used for all of the simulation studies that are carried out. The resistance is 160 ohm, and the inductance is 18.5 mH, and the total resistance is 160 ohm. The switching angles are determined using the SHE technique, and the gate pulses are applied in accordance with the switching angles that have been calculated.

Figure 6 depicts a simulation circuit for a 9-level CHB MLI that was considered for the research project.

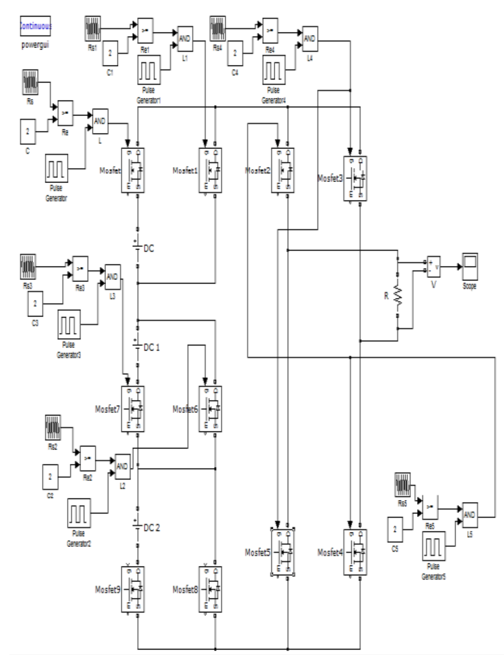


Figure 6: NINE Level MLI.

The MLI with nine levels is seen above, with the semiconductor switches serving as the primary switching element. The circuit is simulated with an RL load applied. The waveforms of the load voltage and the harmonic spectrums are shown in the diagram below.

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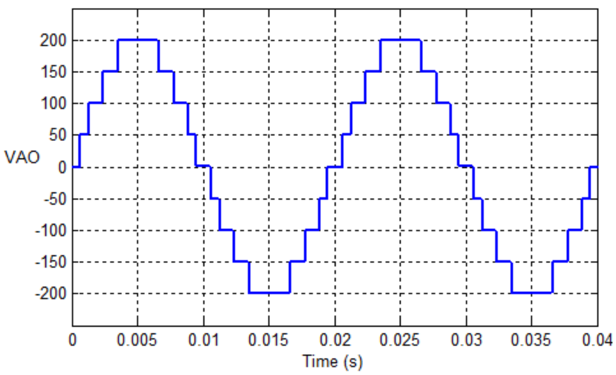

Figure 7: Load Voltage.

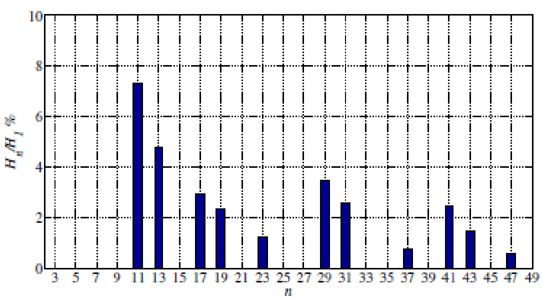

Figure 8: FFT of output voltage.

From Figures 7 and 8, it can be seen that the third, fourth, and seventh order harmonics have been deleted, which is why the values corresponding to these harmonics are displayed as zero in the figures.

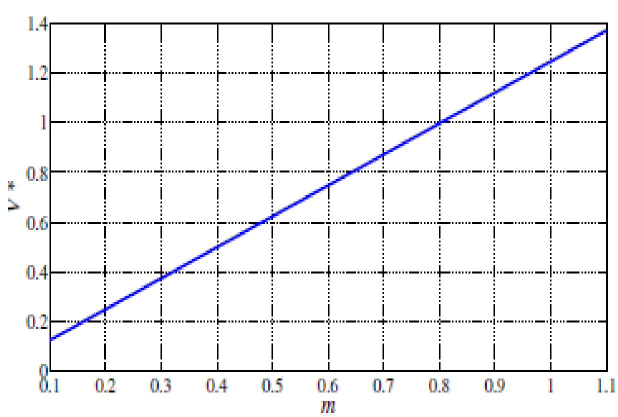

Figure 9: Source Voltage with modulation index.

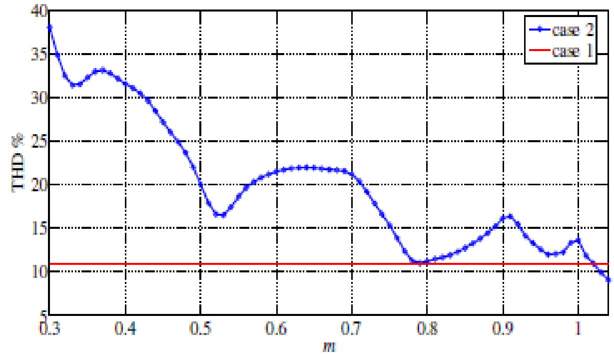

Figure 10: THD with modulation index.

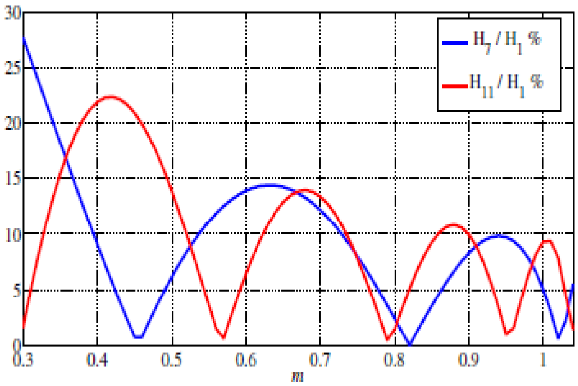

Figure 11: 7th and 11th order harmonics.

The total harmonic distortion (THD) calculated for 9 level MLI is equivalent to 11.78 percent. Because of the removal of low harmonics, the magnitudes of the third, fifth, and seventh harmonics are all equal to zero. The SHE approach was effective in eliminating the specified lower order harmonics from the output waveform of the MLI, indicating that the MLI's output waveform was clean..

IV CONCLUSIONS

The performance of the nine-level CHB MLI using SHE technique is examined in this work, and the findings are reported in the following sections: 1. Three lower order harmonics have been successfully removed from the output waveform by the algorithm. Based on the results of the simulations, it has been shown that the SHE approach is very successful in eliminating the specified lower order harmonics from the voltage waveform output. The application of this technique to any inverter where the reduction of harmonics is required follows as a logical conclusion.

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