Comparison Performance of Multilevel Inverters for Harmonic Reduction in Dynamic Voltage Restorer (DVR) Application

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Abstract: Nowadays, multilevel inverters have become more attractive for their initial usage in high-voltage and high-power applications. This paper presents the analysis and the design of a three-phase cascaded H-Bridge Multilevel inverters (CHB-MLI) for three and five level based on Newton-Raphson technique for harmonic reduction in Dynamic Voltage Restorer (DVR) application. The performance of the inverters output to reduce harmonics is crucial for DVR applications. Two DC sources were applied for two types of CHB-MLI multilevel inverters these types of inverters were used Newton-Raphson technique as their controllers. The main aim of this thesis had been to design, model, construct and conduct laboratory testing upon CHB-MLI of a three and five level prototype for DVR application. The Designed of suitable Multilevel Inverters are very important for DVR purposes so that the AC output voltage waveform of the Inverters have no highly contents of harmonics during energy conversion process from DC to AC of the proposed inverters. The Digital Signal Processing (DSP) TMS320F2812TT was used as a tool in order to create the coding based on Newton-Raphson technique controller.

Key words: Digital Signal processing (DSP) TMS320F2812 · Cascaded multilevel · Controller · Prototype Optimization · Three Phase

INTRODUCTION

Multilevel converters (or inverters) have been used for AC to DC, AC to DC to AC, DC to AC and DC to DC power conversions in high power application such as utility and large motor drive applications [1]. The main purpose of multilevel inverter application is to minimize the harmonic contents of the output inverter waveform without decreasing the inverter power output [2]. The concept of multilevel inverters has been proposed since year 1975 [3]. The main advantages of the multilevel inverters can be categories as lower harmonic distortion, high power quality waveform, lower switching frequency and switching losses, the efficiency is considerably higher and Electromagnetic Interference (EMI) can be minimized using multilevel inverters [4]. A Multilevel inverters are considered as a power electronic devices that can produce a desire voltage output from several level of dc voltage input, an approach for harmonic minimization, have gained worldwide interest [5]. They provide an output with desired waveform that exhibits multiple-steps voltage-levels with minimum distortion. The famous topologies of the multilevel inverter available in the market right now namely, diode-clamped, flying capacitors (FCs) and cascaded H-bridge (CHB) Furthermore, the topology of the FCs type is constructed by a series connection of capacitor-clamped switching cells. Normally in the diode-clamped multilevel inverter that uses a single DC source rather than multiple sources [6]. Finally the Cascaded H-Bridge Multilevel Inverter (CHB-MLI) type, which can be connected either in series or parallel. It so consists of a series of H-bridge cells to synthesize the required voltage from several separate DC sources [7]. The DC sources were applied to the CHB-MLI is from DC supply, batteries, fuel cells, renewable energy or super-capacitor [8]. Thus, CHB-MLI is more beneficial compared to other topologies of the multilevel inverter [9]. Moreover, an appropriate switching angle has to be
generated by using optimizing techniques to control the switching frequencies of each semiconductor switches connected. Based on that, it is very important to propose and develop a suitable multilevel inverters that adopted new control technique using Newton-Raphson interpolation [1] [10]. The minimization of the harmonic profile based on optimization techniques of CHB-MLI for five and three level [11]. The proposed technique offers a new control method for the multilevel inverter to operate in both equal and unequal DC voltage cases.

**Series Voltage Injection Transformers:** Series Voltage Injection Transformer is used to boost the signal from the control circuit for voltage injection purpose as shown in Figure 1. It can be configured either in three single-phase transformer units or one three phase transformer unit.

Normally the series Voltage injection transformer can be divided into two parts namely high voltage side and low voltage side. The distribution system is connected in series with injection transformer at high voltage side, while power circuit of the DVR can be connected at the low voltage side. The basic function of the injection transformer is to increase the voltage supplied by the filtered VSI output to the desired level while isolating the DVR circuit from the distribution network. The transformer winding ratio is pre-determined according to the voltage required in the secondary side of the transformer (generally this is kept equal to the supply voltage to allow the DVR to compensate for full voltage sag. For injection purposes single phase transformers can be used to inject the compensating voltages separately when three phase inverter is used. The DVR performance is totally depend on the rating of the injection transformer, since it limits the maximum compensation ability of the DVR.

**Voltage Source Inverter (VSI):** The main purpose of the VSI is to convert the DC voltage supplied by the energy storage device into an AC voltage. The AC output voltage of the VSI is assumed as low voltage. This AC low voltage produced by VSI then set up to an appropriate voltage through injection transformer. The output voltage of the injection transformer for compensation purposes is considered as high voltage as shown in Figure 2. Generally Pulse-Width Modulated Voltage Source Inverter (PWMVSI) is used in VSI. Thus a VSI with a low voltage rating is sufficient. There are two basic three phase inverter topologies, the popular two-level inverter. Multilevel inverters have recently emerged as an attractive alternative to PWM schemes so that the losses and harmonics associated with fast switching can be eliminated. The implementation of the PWM in the two level inverter is having high content of harmonics than a multilevel inverter. The Inverter is considered as an important components in DVR system. The inverters designed must have no harmonics contents and therefore multilevel inverters are promising low contents of harmonics. Normally, the types of Inverter used in DVR are single or three phase two level inverters.

**Harmonic Spectrum:** When the contributions of individual frequency components of the composite wave are expressed in a graph, it is known as a harmonic spectrum. Harmonic contents are usually described as a percent of the fundamental for a certain component, as shown in Figure 3.

**Types of Controllers and Modulations used in Multilevel Inverter:** There are so many types of controllers that have been used in multilevel inverter, such as:

- Selective Harmonic Elimination Technique PWM (SHE-PWM)
- Space Pulse Width Modulation (SPWM)
- Space Vector Pulse Width Modulation (SVPWM)

**Selective Harmonic Elimination Technique PWM (SHE-PWM):** The selective harmonic elimination PWM (SHE-PWM) technique is based on the fundamental frequency switching theory proposed by Patel in 1974 and it is dependent on the elimination of the defined harmonic content orders. The main idea of this method is based on defining the switching angles of harmonic orders to eliminate and in obtaining the Fourier series expansion of output voltage. An example of output voltage Fourier expansion of an 11-level inverter can be written as depicted in Equation (1).

\[
V(\text{wr}) \sum_{n=1,3,5,...}^{\infty} \frac{4Vdc}{n\pi}(\cos(n\theta_1) + \cos(n\theta_2) + ... + \cos(n\theta_5))\sin(n\text{wr}) \tag{1}
\]

where \( n \) defines the harmonic order at the output voltage of the multilevel inverter.

The required switching angles, to eliminate 3\(^{\text{rd}}\) harmonic orders at the fundamental switching frequency for an 5-level multilevel inverter, can be calculated as given in Equation (2).

\[
\cos(\theta_1) + \cos(\theta_2) + ... + \cos(\theta_5) = 5 \cdot m,
\cos(3 \cdot \theta_3) + \cos(5 \cdot \theta_5) + ... + \cos(5 \cdot \theta_5) = 0 \tag{2}
\]
Fig. 1: The Circuit of Conventional DVR

Fig. 2: Power Circuit of a DVR

Fig. 3: Harmonic spectrum of a sample with distorted wave
Fig. 4: Flowchart of the proposed methodology

Furthermore, the switching angles of $\theta_1$, $\theta_2$ and $\theta_3$ can be determined to minimize the voltage THD ratio, while $m$ defines the modulation index of the modulator. Since the parameters of $E_a$ are non-linear, the values are obtained by using Newton–Raphson Iterations. In fact, the switching angles can be obtained at the values of $\theta_1 = 6.57^\circ$, $\theta_2 = 18.94^\circ$, $\theta_3 = 27.18^\circ$, $\theta_4 = 45.14^\circ$ and $\theta_5 = 62.24^\circ$ by assuming $m$ as 0.8 and solving the equation with Newton–Raphson Iteration.

Moreover, in the application of SHE-PWM, possible switching angles are calculated previously and saved to look-up tables in an independent memory or microprocessor. The main defect of SHE-PWM is the requirement of calculations to determine the switch angles as in fundamental frequency switching method.

However, the Newton–Raphson Iteration is able to solve an equation similar to Equation (2), where the initial values are based on guesses or assumes and the results will not be accurate values. In addition to this, increased DC sources or switching angles will prevent one from obtaining the most accurate solution.

Overall Research Methodology: There are four stages in order to achieve this research methodology as described below. The methodology was selected in order to achieve the objectives of this thesis. The research methodology flow chart and the process of the research project progress is shown in.

Overall Research Methodology: There are four stages in order to achieve this research methodology as described below.

The proposed Scheme of CHB-MLI for Three Phase Five and Three Level: The proposed scheme of a three phase CHB-MLI for five and three level can be constructed as shown in Figure 5 and Figure 6. These topologies have been chosen due to require less power devices compared to the other topologies in the literature. These topologies DC sources supply and based on the series connection of H-bridges for five and three level.

Since the output terminals of the H-bridges were connected in series, the DC sources must be isolated from each other. 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. The resulting AC output voltage was synthesized by the addition of the voltages generated by different H-bridge cells. Each single phase H-bridge generated three voltage levels as $+V_{dc}$, $0$ and $-V_{dc}$ by connecting the DC source to the AC output by different combinations of four switches, $S_1$, $S_2$, $S_3$ and $S_4$, as depicted in the first cell of Figure 5.

Meanwhile, the CHB-MLI that is shown in Figure 6 utilised two separate DC sources per phase and generated an output voltage with five levels. Therefore, in order to obtain $+V_{dc}$, $S_1$ and $S_2$; switches were turned on, whereas the $V_{dc}$ level was obtained by turning on both $S_2$ and $S_1$. The output voltage was 0 by turning on $S_1$ and $S_2$ switches. Moreover, $n$ was assumed as the number of modules connected in series.

Circuit Simulations of the CHB-MLI for five and Three Level based on MATLAB/SIMULINK: MATLAB/SIMULINK software has been used to model the proposed topologies of CHB-MLI for five and three level. The analysis as well as mathematical and engineering problems can be performed Via MATLAB/SIMULINK. It has the characteristics of excellent programming and graphics capabilities. Meanwhile, Simulink is used to model, analyse and stimulate dynamic system block diagram, which is fully integrated with MATLAB, easy and quick to learn, as well as flexible. It has a comprehensive library of blocks that can be used to simulate systems of linear, non-linear or discrete elements.
Fig. 5: The Proposed Topology of a Three-Phase CHB-MLI

Fig. 6: Three-Level CHB-MLI Model
As mentioned earlier the proposed models of CHB-MLI for five and three level were simulating using MATLAB/SIMULINK. The low switching frequency of 5kHz was used to simulate the system. The SIMULINK model consist of DC source of 150V, pulse generator block, three unit of single phase CHB-MLI and R and L as a loads. The values of R = 100km and L = 2.07mH. The system block diagrams based on MATLAB/SIMULINK of a three phase CHB-MLI for five and three level can be illustrated in Figure 7 and Figure 8.

**Fourier Series:** The Fourier series for the total output voltage is as depicted in Equation (3). The two sources circuits contained only odd-numbered harmonic.

\[
V_o = \frac{4V_{dc}}{\pi} \sum_{n=1,3,5,7,9} \frac{[\cos(n\theta_1) + \cos(n\theta_2)]\sin(n\phi_1)}{n}
\]  

(3)

The modulation index \( m \) is the ratio of the amplitude of the fundamental frequency component of \( V_o \) to the amplitude of the fundamental frequency component of a square wave of amplitude \( 2V_{dc} \), which is \( \frac{4V_{dc}}{\pi} \).
The expression equation (4) of is:

$$m_i = \frac{V_i}{2(4V_{dc}/\pi)}$$  \hspace{1cm} (4)

For the two separate DC source inverters, harmonic N was eliminated by using delay angles as;

$$\cos(N\theta_i) + \cos(N\theta_i) = 0$$  \hspace{1cm} (5)

The additional equation derived from (4) for simultaneous solution had been required to eliminate N\textsuperscript{th} harmonic and to meet a specified modulation index.

$$\cos(\theta_i) + \cos(\theta_i) = 2$$  \hspace{1cm} (6)

Besides, these harmonic equations (5) and (6) were transcendental equations. Thus, in order to solve these simultaneous equations, an iterative numerical method was required. Thus, the Newton-Raphson technique was employed to solve these equations.

**Mathematical Technique of Switching via Newton-Raphson:** The values of the conducting angles and were chosen by solving the transcendental equations by using a modulation index formula to obtain suitable modulation index values.; Other angles, which were \(\theta_i\) until \(\theta_{8}\) were obtained by referring to the output waveform of 5-level CHB MLI theory depicted in Figure 7. The procedure of detecting attributes and configuration of a system is called Optimization. For 5-level inverter, only one harmonic was eliminated and here, the harmonics was chosen to be removed.

Thus, the switching angle was determined by solving the transcendental equations via Newton-Raphson technique. These harmonic equations are expressed as;

$$\cos(\theta_i) + \cos(\theta_i) = 2(m_i)$$  \hspace{1cm} (7)

$$\cos(3\theta_i) + \cos(3\theta_i) = 0$$  \hspace{1cm} (8)

By using the following trigonometric identities:

$$\cos(3\theta) = 4\cos^3(\theta) - 3\cos(\theta)$$  \hspace{1cm} (9)

Equations (3.7), (3.8) and (3.9) were changed into polynomials harmonic equations.

Let the variables, $x_i = \cos(\theta_i)$ (10) $x_2 = \cos(\theta_2)$ (11)

Substitute (12) and (13) into (9) and (10) and these equations were obtained,

$$x_i + x_2 = 2m_i$$  \hspace{1cm} (12)

$$4x_i^3 - 3x_i + (4x_2^3 - 3x_2) = 0$$  \hspace{1cm} (13)

By referring to the iterative method, the values of \(x_2\) and \(x_i\) were calculated. Therefore, the values of switching angle for \(\theta_i\) and \(\theta_2\) had been determined as \(x_2\) and \(x_i\) respectively. Then, the angle values \(\theta_i\) until \(\theta_{8}\) were obtained by substituting the values of angle and into these equations.

$$\theta_i = \pi - \theta_i$$  \hspace{1cm} (14)

$$\theta_i = 2\pi - \theta_i$$  \hspace{1cm} (15)

$$\theta_2 = 2\pi - \theta_2$$  \hspace{1cm} (16)

$$\theta_2 = \pi - \theta_2$$  \hspace{1cm} (17)

$$\theta_2 = 2\pi - \theta_2$$  \hspace{1cm} (18)

$$\theta_2 = 2\pi - \theta_2$$  \hspace{1cm} (19)

The switching pattern order of the switches S1, S2, S3, S4, S5, S6, S7 and S8. The pattern was not fixed as long as the switches were turned on and off in the right sequence as to produce the desired output waveform. The switching pattern, which is also known as pattern swapping was used in the five-level CHB-MLI. In this pattern, the first source generated more time in the first half-cycle, while the second source generated a longer time in the second half-cycle.

Therefore, over one complete period, the sources that conducted equal and average power from each source had been similar.

The switching angles of a CHB-MLI for five and three level were calculated using Newton Raphson Technique. The various values of switching angles and their THDv for voltage of a CHB-MLI for five level can be summarized as shown in Table 1.

**Level Multilevel Inverters:** The equations for level five that was based on Fourier series are described below:
Table 1: The values of switching angles and voltage THD of a CHB-MLI for 5-level

<table>
<thead>
<tr>
<th>Mi</th>
<th>Mi=0.84</th>
<th>THD_{phase}</th>
<th>Mi=0.68</th>
<th>THD_{phase}</th>
</tr>
</thead>
<tbody>
<tr>
<td>ℓ1</td>
<td>17.06</td>
<td>16.9949</td>
<td>8.774</td>
<td>29.56</td>
</tr>
<tr>
<td>ℓ2</td>
<td>43.53</td>
<td>16.9949</td>
<td>68.16</td>
<td>29.56</td>
</tr>
<tr>
<td>ℓ3</td>
<td>136.47</td>
<td>16.9949</td>
<td>111.85</td>
<td>29.56</td>
</tr>
<tr>
<td>ℓ4</td>
<td>1630</td>
<td>16.9949</td>
<td>171.226</td>
<td>29.56</td>
</tr>
<tr>
<td>ℓ5</td>
<td>1970</td>
<td>16.9949</td>
<td>188.774</td>
<td>29.56</td>
</tr>
<tr>
<td>ℓ6</td>
<td>2240</td>
<td>16.9949</td>
<td>248.15</td>
<td>29.56</td>
</tr>
<tr>
<td>ℓ7</td>
<td>316.47</td>
<td>16.9949</td>
<td>291.845</td>
<td>29.56</td>
</tr>
<tr>
<td>ℓ8</td>
<td>3430</td>
<td>16.9949</td>
<td>351.226</td>
<td>29.56</td>
</tr>
</tbody>
</table>

Table 2: The values of switching angles and voltage THD of a CHB-MLI, for three level

<table>
<thead>
<tr>
<th>Mi</th>
<th>Mi=0.84</th>
<th>THD_{phase}</th>
<th>Mi=0.68</th>
<th>THD_{phase}</th>
</tr>
</thead>
<tbody>
<tr>
<td>ℓ1</td>
<td>17.06</td>
<td>35.55%</td>
<td>8.774</td>
<td>48.60%</td>
</tr>
<tr>
<td>ℓ2</td>
<td>43.53</td>
<td>35.55%</td>
<td>68.16</td>
<td>48.60%</td>
</tr>
<tr>
<td>ℓ3</td>
<td>136.47</td>
<td>35.55%</td>
<td>111.85</td>
<td>48.60%</td>
</tr>
<tr>
<td>ℓ4</td>
<td>1630</td>
<td>35.55%</td>
<td>171.226</td>
<td>48.60%</td>
</tr>
</tbody>
</table>

\[
f(t) = f_{\theta_i}(t) = \frac{2V_{dc}}{\pi} \sum_{h=1}^{\infty} \cos(h \theta_i)
\]  

(20)

where:

\(V_{dc}\): Voltage of each voltage source that was in unity

\(\theta_i\): The switching angles

\(h\): The harmonic orders

From (21) and (20), four equations were resulted in eliminating the 1\textsuperscript{st} and harmonic.

\[V_{dc} = V_1\]

(21)

\[\frac{2V_{dc}}{\pi}(\cos \theta_i) = h_i\]

Equations (3.19) and were for the harmonics that should have been eliminated, The DC sources were constant, so;

\[V_{dc} = 2V_1\]

(22)

\[M = \frac{h_i}{2V}\]

(23)

The modulation index and the voltage used in these calculations was in per unit. From (21) to (23), the nonlinear equations were calculated.

\[\cos(\theta_i) = \frac{\pi}{2}\]

(24)

\[\cos(3\theta_i) = 0\]

(25)

\[\cos(3\theta_i) = \sin(0.84)\]

(26)

By using the following trigonometric identities:

\[\cos(3\theta) = 4\cos^3(\theta) - 3\cos(\theta)\]

(27)

Equations (25), (26) and (27) are changed into polynomials harmonic equations. Let the variables,

\[X_i = \cos(\theta_i)\]

(28)

Substitute (28) and (27) into (26) and (3.23) and get these equations,

\[\theta_i = \pi - \theta_1\]

(29)

\[\theta_i = \pi - \theta_2\]

(30)

The solutions of the above equations are shown below.

The values of the conducting angles \(\theta_1\) and \(\theta_2\) can be chosen by solving the transcendental equations using a modulation index of 0.84. Other angles which are \(\theta_i\) until \(\theta_4\) can be obtained by referring the output waveform of 3 levels CHB MLI theory.

\[X_1 = 2(0.84)\]

(31)

\[(4X_1^3 - 3X_1) = 0\]

(32)

By solving (33) and (32), the function equation obtained is;

\[F(X) = 20.16X_1^2 - 33.872X_1 + 13.96\]

(33)

By referring to the iterative method, 2 iteration calculations have been used. The calculated value of \(X_1\) = 0.956 while the value \(X_1\) = 0.725. Therefore, the values of switching angle for \(\theta_1\) and \(\theta_2\) are 17.06\degree and 43.53\degree respectively. Then, the angle values \(\theta_i\) until \(\theta_4\) can be obtained by substituting the values angle \(\theta_1\) and \(\theta_2\) into these solutions of the above equations (29)-(30) are shown below;

\[\theta_3 = 136.47\degree, \theta_4 = 163\degree\]

Table 2 shows the calculation of the various values of switching angles and THD for voltage of a CHB-MLI for three level.

Prototype Development of a Three-Phase CHB-MLI for Five and Three Level Experiment Circuits: With regard to the hardware connection of the system, a prototype
model of the CHB-MLI system for five and three level were constructed and tested to verify the effectiveness of the proposed systems operations as shown in the experimental setup for five and three level. The full system of the CHB-MLI for five and three level can be illustrated in Figure 9 and Figure 10. The overall system comprised of DC power supply, three-phase five-and three level of CHB-MLI with DSP-based control circuit and connected RL loads and a personal computer (PC).

Simulation Results for Optimization of a Three-Phase Five Level CHB-MLI model with MI= 0.84: In this simulation operation the duration of time was equal 0.02s of one cycle. The value of MI=0.84 and the switching angles has been calculated and was simulated with switching angles \( \theta_1 = 17.06^\circ \) and \( \theta_2 = 43.53^\circ \) at the upper and lower switches of CHB-MLI. The timing diagram of every phases of phases A, B and C. Each phase of a CHB-MLB for five has eight switches namely S1, S2, S3, S4, S5, S6, S7 and S8. The both upper and lower sides has four switches. The output voltage waveform of CHB-MLI for five level of PhaseA, Phase B and Phase C can be observed as shown in Figure 11.

The harmonics spectrum with MI is equal 0.84 of a CHB-MLI for five levels can be illustrated in Figure 12. The THD values equivalent to 16.86% before filtering. This values is meet to IEC standard.
Simulation Results of a Three-Phase of CHB-MLI for Five Level MI=0.68: The simulation results of this study using the same simulation model of CHB-MLI for five level. However it MI has changed to 0.68. The value of MI=0.68 was taken for switching angles calculation. The switching angles obtained are equal $\theta_1 = 8.774^\circ$ and $\theta_2 = 68.155^\circ$ besides, one period equalled to 0.02s was taken and simulated with MI of 0.68. Figure 13 shows the non-optimization voltage output waveform of a CHB-MLI for 5-level of Phases A, B and C respectively. The Non-optimization voltage output waveforms for each phase of CHB-MLI for five level had been not smooth as the calculation of the switching angles was inaccurate. In case of Non-Optimization voltage output waveform is considerably high content of harmonics and Figure 14 shows the harmonic spectrum of the non-optimization voltage output waveform of CHB-MLI with THD values equivalent to 29.56%.

Simulation Results for Optimization of a Three-Phase Three level of a CHB-MLI model with MI=0.84: In this simulation operation the duration of time was equal 0.02s of one cycle. The values of MI=0.84 and the switching angles has been calculated and was simulated with switching angles $\theta_1 = 17.06^\circ$ at the upper and lower switches of CHB-MLI for three level. The timing diagram of each phases of phase A, B and C. There are eight switches for each phase such as S1, S2, S3, S4, S5, S6, S7 and S8. The upper sides has four switches and another four switches at the lower sides. The optimization of the
Fig. 13: Output Non-Optimization Voltage of a CHB-MLI for five level with MI=0.67.

Fig. 14: Non-Optimization Harmonic Spectrum for Voltage of CHB-MLI for five level with MI=0.68.

Fig. 15: Output for Three Level optimization Inverter Mi = 0.84
CHB-MLI can obtained the smooth output voltage waveform of three-level CHB-MLI for Phases A, B and C as shown in Figure 15 respectively. The output voltage waveforms for each phase of CHB-MLI had been very smooth due to accurate calculation of switching angles. The harmonic spectrum of optimization voltage output waveform of CHB-MLI for three level can be seen in Figure 16 with THD values equivalent to 16.86% before filtering. This values is meet to IEC standard.

Non-Optimization of a Three Phase of a CHB MLI for Three-Level with MI=0.68: The second non-optimization simulation of a CHB-MLI for three level was simulated at MI =0.68 with the duration of time at one cycle is equal 0.02s is also created. The switching angles used in this simulation $\theta_1 = 8.774^\circ$.

The non-optimization simulation of a CHB-MLI was simulated at MI =0.68. The switching angles used in this simulation $\theta_2$ are. Figure 17 shows the output waveform of CHB-MLI and harmonic content THD=48.60% respectively.

Optimization Experimental Results of a Three-Phase 5-Level CHB-MLI MI=0.84: In order to determine if the simulation results are in good agreement with the experimental results, a source code based on Newton-Raphson controller for optimization of a three-phase five-level CHB-MLI had been developed. The developed source codes programming, were then stored into DSPTMS320F2812. The DSPTMS320F2812 card was then interfaced with the proposed prototype of CHB-MLI.

In the source code programming, one cycle for the duration of time was equal to 0.02s with MI=0.84. Meanwhile, the values of the switching angles were $\theta_1 = 17.06^\circ$ and $\theta_2 = 43.53^\circ$ of CHB-MLI. Figure 19 shows the optimization voltage output waveform of 5-level CHB-MLI for Phases A, B and C respectively. The optimization of voltage output waveforms for each phase of CHB-MLI had been very smooth due to accurate calculation of the switching angles. Figure 20 shows the harmonic spectrum of the optimization of voltage output waveform for CHB-MLI with THD values equivalent to 15.6%.

Non-OptimizationExperimental Results of a Three-Phase Five-Level CHB MLI MI=0.68: In this case of non-optimization of a CHB-MLI, a source code of non-optimization, was developed and stored in DSPTMS320F2812. The interface between DSPTMS320F2812 and CHB-MLI produced a non-optimization waveform. The MI used in this technique was equal to 0.68 with switching angles $\theta_1 = 8.774^\circ$ and $\theta_2 = 68.16^\circ$.

Besides Figure 21 shows the non-optimization voltage output waveform of 5-level CHB-MLI for Phases A, B and C respectively. The non-optimization voltage output waveforms for each phase of CHB-MLI were not smooth due to inaccurate calculation of the switching angles. Figure 22, on the other hand, shows the harmonic spectrum of the non-optimization voltage output waveform of CHB-MLI with THD value equivalent to 28.5%.
Fig. 17: Output for Three Level inverter $M_i = 0.68$

Fig. 18: Optimization Harmonic Spectrum for Voltage of 3-level CHB-MLI with $M_i=0.68$

Fig. 19: Optimization of Voltage Output Waveform of 5-Level CHB-MLI with $M_i=0.84$
Fig. 20: Optimization Harmonic Spectrum of Voltage Output Waveform of CHB-MLI with \( MI = 0.84 \)

Fig. 21: Non-optimization Voltage Output Waveform of 5-Level CHB-MLI with \( MI = 0.68 \)

Fig. 22: Non-optimization Harmonic Spectrum of Voltage Output waveform of CHB-MLI with \( MI = 0.68 \).

**Optimization Experimental Results of a Three-Phase for Three-Level CHB-MLI, MI=0.84:** To describe the operation of optimization of a three-phase three-level CHB-MLI, a source code was developed. In this operation, the MI was set at 0.84 with switching angles \( \theta_i = 17.955 \). By using the same method for non-optimization
Fig. 23: Three Level Three Phase MI = 0.84

Fig. 24: Optimization Harmonic Spectrum of voltage three level of CHB-MLI with MI=0.84

Fig. 25: Three Level Three Phase MI = 0.68
technique, the developed source codes were stored in the DSP TMS320F2812. Figure 23 shows the optimization voltage output waveform of 3-level CHB-MLI for Phases A, B and C respectively. The optimization of voltage output waveforms for each phase of CHB-MLI had been less smooth rather than the voltage output waveform for five levels. Figure 24 shows the harmonic spectrum of the optimization of voltage output waveform for CHB-MLI with THD values equivalent to 34.2%.

Non-Optimization Experimental Results of a Three-Phase Three-Level CHB-MLI MI=0.68: To describe the operation of non-optimization of a three-phase three-level CHB-MLI, a source code was developed. In this operation, the MI was set at 0.68 with switching angles $\theta = 17.955$. By using the same method for non-optimization technique, the developed source codes were stored in the DSP TMS320F2812. Figure 25 shows the non-optimization voltage output waveform of 3-level CHB-MLI for Phases A, B and C respectively. The non-optimization of voltage output waveforms for each phase of CHB-MLI had been less smooth rather than the voltage output waveform for three level. Figure 26 shows the harmonic spectrum of the non-optimization of voltage output waveform for CHB-MLI with THD values equivalent to 34.2%.

CONCLUSION

This work conducted a theoretical analysis, simulations and experimental on CHB-MLI for five and three level topologies with a new control algorithm proposed. Both the five and three level of a CHB-MLI were successfully developed and tested. In order to run the simulation and hardware a controller using Newton-Raphson technique has been applied to CHB-MLI for five and three level. The low switching frequency control schemes operation can be considered to be implemented in the CHB-MLI for five and three level. The outcome of the results from simulation and experimental showed that the higher level of inverter it will produce lower harmonics contents of the CHB-MLI.

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