Validation of a Three-Phase Cascaded Multilevel Inverter based on Newton Raphson (N.R.)

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Abstract

Objective: This paper discusses the configuration three-phase Cascaded H-Bridge Multilevel Inverter (CHBMLI) based on Newton Raphson (N.R.) method to produce five-levels of output voltage by reduce Total Harmonic Distortion (THD).

Method: The proposed method had been comprised of 5-level multilevel inverter, while the control system was based on the Newton Raphson (N.R.) method. Moreover, the main purpose of the research was to investigate the effectiveness of the proposed method by using NR for harmonic analysis in high voltage electrical distribution system. Besides, the optimization of the controller based on modulation indexes was employed in order to optimize and non-optimize the switching angle of the CHBMLI for different modulation indexes.

Findings: An inverter is used to convert DC power generator from the DC supply into AC power. The five-level inverter resulting in increased voltage levels of the output waveform. As the levels of output waveform increase, the percentage of THD reduced and switching losses decreased to improves power quality have been done compared with conventional three phase Dc supply connected PWM cascaded H-bridge multilevel inverter. Based on Newton Raphson (N.R.) five-level of output voltage is produced by the inverter zero, +1/2Vdc, +Vdc, -1/2Vdc and –Vdc.

Improvements: Apart from that, the proposed scheme was modelled with MATLAB software and the Simulation results were verified via hardware experimental by using Digital Signal Processing (DSP) TMS320F2812. The experimental results showed that the proposed method had been effective in verifying the NR control in terms of Total Harmonic Distortion (THD).

Keywords: Cascaded H-Bridge Multilevel Inverter (CHBMLI), Digital Signal Processing (DSP) TMS320F2812, Newton Raphson (N.R.)

1. Introduction

Multilevel inverter has become a significant element in generating high power and high voltage application. The multilevel inverter requires a number of isolated Dc supplies, each of which feeds a power cell\(^1\)\(^-3\). Besides, the modular structure for a multilevel inverter is composed of multiple units of identical H-bridge power cell, which is an effective means for reducing the manufacturing cost\(^4\). In addition, the output voltage inverter waveform is generated by several small voltage levels and they are distributed sinusoidal over time; resulting in low Total Harmonic Distortion (THD), and therefore, \(\text{dv/dt}\) can be used to overcome the issue\(^5\)\(^-6\). Besides, multilevel inverters have three topologies: 1. Cascaded H-Bridge (CHB), 2. Diode–Clamped (NPC) and 3. Flying Capacitors (FC) Cells, with separated DC sources\(^7\)\(^-9\). Meanwhile, the power cells are connected to the cascaded H-bridge to withstand the high Ac voltage, whereas the number of voltage levels in a cascaded H-Bridge inverter, \(m\), can be determined from \(m = (2H + 1)\), where \(H\) is the number of H-bridge cells per phase. Furthermore, the power cells in an inverter phase are normally connected to the cascaded H-bridge on their Ac output side to achieve high voltage operation and low
harmonic distortion\(^1\). On the other hand, a model of single phase cascaded H-bridge multilevel inverter based on Newton-Raphson (NR) method with optimized switching angle had been developed by\(^1\). Besides, the analyses of harmonic reduction in a cascaded H-bridge multilevel inverter based on Newton Raphson (NR) and Genetic Algorithm (GA) by using controller harmonic elimination Pulse Width Modulation (SHE-PWM) switching method had been compared by\(^1\). Meanwhile, the solar photovoltaic system employed for (CHB) Five-level inverter with Dc voltage supplied from battery storage AC supply load by using Adaptive Neuro Fuzzy Inference (ANFIS) based on Newton-Raphson (NR) method exhibited lower harmonic distortion\(^1\). Furthermore, a new cascaded H-bridge with seven-level inverter that was implemented to reduce switches topology by using Selective Harmonics Elimination Stepped Waveform (SHESW) method had lowered the harmonics and improved the efficiency\(^1\). Next, a Particle Swarm Optimization (PSO) method in cascaded five-level inverter was implemented by solving non-linear equations through the use of the developed PSO algorithm\(^1\). Besides, seven-level output voltage used in a stand-alone PV was improved by controlling the Optimized Harmonic Elimination Stepped Waveform (OHESW) technique, which also looked into the quality of the output waveform. In addition, the Newton-Raphson (NR) method was applied in solving equations to produce the least total harmonic distortion\(^1\). On top of that, many types of dc storage have been applied to multilevel inverters, such as battery; fly wheel, and other related dc sources, which meet the three phases of the dc source with their charges, as well as in reducing harmonic distortion in the selected network. Moreover, the design of a dynamic model multilevel inverter based on Super Capacitor, Dc bus, and various losses has been discussed by\(^1\), whereas a five-level diode-clamped inverter based on Super Capacitor and battery investigation with PV energy was experimented\(^1\). Furthermore, a three-level inverter with Third Harmonic Injection PWM (THIPWM) dynamic performance of Super Capacitor/battery was proposed\(^1\). Nevertheless, this paper proposes a model that employed the Newton Raphson (NR) method to control the three-phase cascaded H-bridge five-level inverter based on modulation indexes, as illustrated in Figure 1. Besides, the Digital Signal Processing (DSP) TMS320F2812 hardware was implemented in the 5-level (CHB) inverter. The design simulation and the DSP experimental results were tested to determine if they had been able to verify the retrieved Newton Raphson (NR) control in terms of THD.
2. Five-Level Cascaded H-Bridge (CHB) Inverter Topology

Sine wave voltage is produced through a series of H-bridge inverters connected to a multilevel converter architecture based on a series of inverters that consist of three phases of H-Bridge. Each cell is supplied by the converter from the DC source. In Figure 2 the structure is related to the level of five inverters that consist of 8 switches in one leg, gates cascaded H-bridge in three-phased inverter with arm. Output $2N + 1$ is shown in Figure 3, whereby the output voltage wave forms five-level. In order to reduce the total harmonic distortion, the switching angles can be optimized by adjusting them. Compared to flying capacitor or diode imposed, the development of the inverter is cheaper. This is because; multi-level inverters are very small in the number of its components. Figure 2 shows the Cascade H-bridge, where all the low voltage H-bridge part had its own voltage source DC-link. However, the control structure performed better than the previous ones. Phase ‘A’ are $(Sa_1, Sa_1)$, $(Sa_2, Sa_2)$, $(Sa_3, Sa_3)$, $(Sa_4, Sa_4)$ and this was similar for B and C phases for cascade H-bridge.

2.1 5-Level Multilevel Inverters

The equations for level five that was based on Fourier series are described below:

$$f(t) = f_{\theta_1}(t) + f_{\theta_2}(t) = \frac{2V_{dc}}{\pi} \sum_{h=1}^{\infty} \left[ \cos(h\theta_1) + \cos(h\theta_2) \right]$$

where:

- $V_{dc}$: Voltage of each voltage source that was in unity
- $\theta_i$: The switching angles
- $h$: The harmonic orders

From $(2-1)$, four Equations were resulted in eliminating the 1st and $i^{th}$ harmonic.

$$V_{dc} = V_1 + V_2$$

$$\frac{2V_{dc}}{\pi} \left( \cos \theta_1 + \cos \theta_2 \right) = h_1$$

$$\frac{2V_{dc}}{\pi} \left( \cos 3\theta_1 + \cos 3\theta_2 \right) = h_3$$

Equations (2) and (3) were for the harmonics that should have been eliminated, so (3) should equal to zero. The DC sources were constant, so

$$V_{dc} = 2V_1$$

$$M = \frac{h_1}{2V}$$

The modulation index, and the voltage used in these calculations was in per unit. From (2) to (5), the nonlinear equations were calculated.

$$\cos(\theta_1) + \cos(\theta_2) = \frac{\pi}{2}$$

$$\cos(3\theta_1) + \cos(3\theta_2) = 0$$

3. Proposed Control Newton Raphson (N.R.) Method of a (CHB-MLI)

To calculate the stepped switches angles by using Newton Raphson method and to calculate THD value. In this paper, stepped angles, which are calculated for 5-level CHB-MLI were implementation. Switching angles can be computed to produce the desired fundamental voltage $V_1 = M_i \left( 4sV_{dc}/\pi \right)$ while eliminating the 3rd harmonics by making there equations equal zero. The transcendental nonlinear equations reflecting each harmonics are solved to compute the switching angles $\theta_1$ and $\theta_2$ of the inverter based on $M_i 0.84$ as shown in Table 1. The value of the switching angles $\theta_3 - \theta_8$ are calculated in degree unit to represent these angles in pulse generation of 5-levels output waveform CHB MLI theory in Figure 2.

$$\cos(3\theta_1) + \cos(3\theta_2) = 0$$

$$\cos(3\theta_3) + \cos(3\theta_8) = 2(0.84)$$

Use the flowing equation trigonometric:

$$\cos(3\theta) = 4\cos^3(\theta) - 3\cos(\theta)$$

Equations (12), (13), and (14) solving the harmonic elimination equations.

$$X_1 = \cos(\theta_1)$$

$$X_2 = \cos(\theta_2)$$

Substitute (15) and (16) into (12) and (13) and get these equations,
\[ X_1 + X_2 = 2(0.84) \]  \hspace{1cm} (17) \[ (4X_1^3 - 3X_1) + (4X_2^3 - 3X_2) = 0 \]  \hspace{1cm} (18)

The Newton Raphson method has been used in solving these equations (17) and (18) \[ F(X) = 20.16X_2^2 - 33.872X_2 + 13.96 \]  \hspace{1cm} (19)

These calculations value of X1 = 0.956 and the value X2 = 0.725 are done by Newton’s algorithm for determining the switching angles of CHB-MLI. In addition, the Algorithm of the Mathematical Model is used to calculate the Total Harmonic Distortion (THD) voltage. Selective Harmonic Elimination (SHE) is a technique in which the switching angles \( \theta_1 \) 17.060 and \( \theta_2 \) 43.530 of an inverter are calculated offline so as to cancel out different ordered harmonics. The switching angles value \( \theta_3 \) \( \theta_8 \) can be obtained by using switching angle \( \theta_1 \) and \( \theta_2 \) of these Equations:

\[ \theta_3 = \pi - \theta_2 \]  \hspace{1cm} (20)

The solutions of the above equations are shown below

| \( \theta_1 \) | \( \theta_2 \) | \( \theta_3 \) | \( \theta_4 \) | \( \theta_5 \) | \( \theta_6 \) | \( \theta_7 \) | \( \theta_8 \) |
|---|---|---|---|---|---|---|---|
| Ma | \( 0.84 \) | 17.06° | 43.53° | 136.47° | 163° | 197° | 224° | 316.47° |
| | \( 0.68 \) | 8.77° | 68.16° | 111.85° | 171.226° | 188.774° | 248.15° | 291.845° |

4. Simulink Models and Results

The Newton Raphson algorithm has been implemented by use MATLAB Simulink software to calculate optimum switching angle and THD for the output voltage. The values of angles and THD for optimize and non-optimize based on MI. The 3-phase 5-levels of CHB-MLI have been simulated by MATLAB Simulink software to validate the

![Model three phase five-level cascaded H-bridge multilevel inverter](image-url)
Phase A, output waveform S1, S2, S3, and S4, $M_a=0.84$ for $\theta_1=17.06^\circ \theta_2=43.53^\circ$.

Phase B, output waveform S5, S6, S7, and S8 $M_a=0.84$ for $\theta_1=17.06^\circ \theta_2=43.53^\circ$.

Phase A, output waveform S5, S6, S7, and S8, $M_a=0.84$ for $\theta_1=17.06^\circ \theta_2=43.53^\circ$.

Phase C, output waveform S1, S2, S3, and S4, $M_a=0.84$ for $\theta_1=17.06^\circ \theta_2=43.53^\circ$.

Phase B, output waveform S1, S2, S3, and S4, $M_a=0.84$ for $\theta_1=17.06^\circ \theta_2=43.53^\circ$.

Phase C, output waveform S5, S6, S7, and S8, $M_a=0.84$ for $\theta_1=17.06^\circ \theta_2=43.53^\circ$.

**Figure 5.** Three phase optimization switching patterns of cascaded H-Bridge multilevel inverter.
Validation of a Three-Phase Cascaded Multilevel Inverter based on Newton Raphson (N.R.)

Figure 6. Output Optimization Voltage 5-level inverter based on Modulation Index ma=0.84.

Figure 7. FFT Analysis Output Optimization Voltage 5-level inverter ma=0.84.

Phase A, output waveform S5, S6, S7, and S8 ma=0.68 for $\theta_1 = 8.774^\circ \theta_2 = 68.155^\circ$.

Phase B, output waveform S1, S2, S3, and S4 ma=0.68 for $\theta_1 = 8.774^\circ \theta_2 = 68.155^\circ$.

Phase A, output waveform S1, S2, S3, and S4 ma=0.68 for $\theta_1 = 8.774^\circ \theta_2 = 68.155^\circ$.

Phase B, output waveform S5, S6, S7, and S8 ma=0.68 for $\theta_1 = 8.774^\circ \theta_2 = 68.155^\circ$.
calculated THD and calculate the value of MI related to the Dc voltage source 100 V dc as shown in Figure 4. Pulse generator percentage is same for all symmetrical switches for each phase of three-phase inverter. Five-level 3-phase voltage output 200v and frequency 50 Hz for inverter base on (NR).

4.1 Three Phase Model Optimization Five-Level CHB Multilevel Inverter

The simulation, Mi equal 0.84 is taken 0.02 period and phase delay is 0.00094 which is switching angle 1 for obtain +Vdc, switches S1 and S4 are turned on, whereas –Vdc can be obtained by turning on switches S2 and S3.

For the phase delay is taken as 0.00242 which is for switching angle 2. Each inverter cell can generate three different voltage outputs, +Vdc, 0, and –Vdc by connecting the dc source to the ac output by different combinations of the four switches, S1, S2, S3, and S4. The of 3-phase MLI optimization for switching patterns are shown in Figure 5.

The proposal three phase five level cascaded H-Bridge multilevel inverter based on modulation index optimization output voltage as shown in Figure 6. Moreover, elimination of the 1st and the 3rd orders resulted in THD = 16.86% with a modulation index that equaled to 0.84 as shown in Figure 7.

4.2 Three Phase Model Non-Optimization Five-Level CHB Multilevel Inverter

The simulation modelling cascaded H-Bridge multilevel inverter output voltage five level non optimization waveform, modulation index equal 0.68, is taken 0.02 period and phase delay is 0.000488 which is switching angle 1 for obtain +Vdc, switches S1 and S4 are turned on, whereas –Vdc can be obtained by turning on switches S2 and S3. For the phase delay is taken as 0.003787 which is for switching angle 2. Each inverter cell can generate three different voltage outputs, +Vdc, 0, and –Vdc by connecting the dc source to the ac output by different combinations of the four switches, S1, S2, S3 and S4. The of 3-phase multilevel inverter non-optimization is shown in Figure 8.

The proposal three phase five level cascaded H-Bridge multilevel inverter based on modulation index non optimization output voltage as shown in Figure 9. Moreover, elimination of the 1st and the 3rd orders resulted in THD = 29.56% with a modulation index that equaled to 0.68 as shown in Figure 10.

5. Experimental Verification

The proposed prototype of three phase five-level cascaded H-bridge multilevel inverter using DSP TMS320F2812 based on Newton Raphson method have been built. In this TMS320F2812 board control generate pulse the switching signal for the proposed inverter. 100 V dc sources are selected. The 5-level MLI of output voltage is 200 volts and frequency equal 50 Hz. The gate drive for five levels three phase cascaded H-bridge multilevel inverter was designed with combination gate drive circuit cascaded H-bridge multilevel inverter. This gate drive in order has been tested using DSP TMS320F2812 implementa-
tion based software coding to get the output waveform from IGBT as seen in Figure 11. These gate drives are designed that output voltage from GPIO is approximately to 5 V and through IGBT output voltage has been step up transformer that 5 V into 15 V which is switching pulses waveform used for load such as a resistor, 100 kΩ. This DSP TMS320F2812 source code project has been changed the frequency reference from 150 MHz to 50 Hz.
5.1 Three Phase Experimental Optimization Five-Level CHB Multilevel Inverter

The experimental result proposed of three phase five-level cascaded H-bridge multilevel inverter using DSP TMS320F2812 based on Newton Raphson method. In this prototype optimization of output voltages with a modulation index that equaled 0.84 for switching patterns from source code for phases A, GPIOB8 S1A, GPIOA1 S2A, GPIOA2 S3A, GPIOA3 S4A, GPIOA4 S5A, GPIOA5 S6A, GPIOA6 S7A, and GPIOA7 S8A are presented in Figure 12 Phase A.

Phase A switching pattern for S1, S2, S3 and S4 Ma=0.84 for $\theta_1 = 17.06^\circ, \theta_2 = 43.53^\circ$.

Phase B Switching pattern for S1, S2, S3 and S4 Ma=0.84 for $\theta_1 = 17.06^\circ, \theta_2 = 43.53^\circ$.

Phase A switching pattern for S5, S6, S7 and S8 Ma=0.84 for $\theta_1 = 17.06^\circ, \theta_2 = 43.53^\circ$.

Phase B Switching pattern for S5, S6, S7 and S8 Ma=0.84 for $\theta_1 = 17.06^\circ, \theta_2 = 43.53^\circ$.

For switching patterns Ma=0.84, for switching patterns from source code for phases B, GPIOA8 S1B, GPIOA9 S2B, GPIOA10 S3B, GPIOA11 S4B, GPIOA12 S5B, GPIOA13 S6B, GPIOA14 S7B and GPIOA15 S8B are presented in Figure 12 Phase B.

For switching patterns Ma=0.84, for switching patterns from source code for phases C, GPIOB0 S1C, GPIOB1 S2C, GPIOB2 S3C, GPIOB3 S4C, GPIOB4 S5C, GPIOB5 S6C, GPIOB6 S7C, and GPIOB7 S8C are presented in Figure 12 Phase C.
5.2 Three Phase Experimental Non Optimization Five-Level CHB Multilevel Inverter

The experimental result proposed of three phase five-level cascaded H-bridge multilevel inverter using DSP TMS320F2812 based Newton Raphson method. In this prototype non optimization of output voltage with modulation index equal 0.68 for switching patterns from source code for phases A, GPIOB8 S1A, GPIOA1 S2A, GPIOA2 S3A, GPIOA3 S4A, GPIOA4 S5A, GPIOA5 S6A, GPIOA6 S7A, and GPIOA7 S8A are presented in Figure 15 phases A.

Besides, the experimental result of the output waveform for the proposed three-phase five-level cascaded H-Bridge multilevel inverter based on modulation index with non-optimized output voltage is portrayed in Figure 13. Moreover, elimination of the 1st and the 3rd orders resulted in THD = 15.6% with a modulation index that equaled to 0.84 as shown in Figure 14.

Phase C Switching pattern for S1, S2, S3 and S4 Ma=0.84 for \( \theta_1 = 17.06^\circ \) \( \theta_2 = 43.53^\circ \).

Phase C Switching pattern for S5, S6, S7 and S8 Ma=0.84 for \( \theta_1 = 17.06^\circ \) \( \theta_2 = 43.53^\circ \).

Figure 12. Three phase optimization switching patterns source code of cascaded H-Bridge multilevel inverter.

Figure 13. Output voltage 5-level cascaded multilevel inverter Ma=0.84.

| Harmonics | 0 | THD | 15.6% |
|-----------|---|-----|-------|
| 1 | 5% |
| 3 | 10% |
| 5 | 5% |
| 7 | 5% |
| 9 | 5% |
| 11 | 5% |
| 13 | 5% |
| 15 | 5% |
| 17 | 5% |

Figure 14. FFT analysis output voltage 5-level inverter Ma=0.84.
For switching patterns non optimization $Ma=0.68$, for switching patterns from source code for phases B, GPIOA8 S1B, GPIOA9 S2B, GPIOA10 S3B, GPIOA11 S4B, GPIOA12 S5B, GPIOA13 S6B, GPIOA14 S7B, and GPIOA15 S8B are presented in Figure 15 phase B.

For switching patterns non-optimization $Ma=0.68$, for switching patterns from source code for phases C, GPIOB0 S1C, GPIOB1 S2C, GPIOB2 S3C, GPIOB3 S4C, GPIOB4 S5C, GPIOB5 S6C, GPIOB6 S7C, and GPIOB7 S8C are presented in Figure 15 phase C.

Besides, the experimental result of the output waveform for the proposed three-phase five-level cascaded H-Bridge multilevel inverter based on modulation indexes with non-optimized output voltage is portrayed in Figure 16. Moreover, elimination of the 1st and the 3rd orders resulted in THD = 28.5% with a modulation index that equaled to 0.68 as shown in Figure 17. Figure 18 presents carve the comparison of modulation index inverters to order total harmonic distortion.
Validation of a Three-Phase Cascaded Multilevel Inverter based on Newton Raphson (N.R.)

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5. Conclusion

A novel three-phase cascaded H-bridge five-level inverter based on Newton Raphson method had been proposed. Besides, the switching scheme algorithm source code, as discussed, had been developed. Moreover, the Newton-Raphson method had effectively reduced the total harmonic distortion THD optimization of value to be less than that of non-optimized by solving the non-linear equations from the switching angles. Thus, the proposed simulation and the experiment of three-phase cascaded H-bridge multilevel inverter by using DSP TMS320F2812 based on modulation indexes had been successfully carried out and achieved the objective of the paper.

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![Phase C Switching pattern for S1, S2, S3 and S4 Ma=0.68 for θ₁=8.774° θ₂=68.155°.](image1)

![Phase C Switching pattern for S5, S6, S7 and S8 Ma=0.68 for θ₁=8.774° θ₂=68.155°.](image2)

**Figure 15.** Three phase non-optimization switching patterns source code of cascaded H-Bridge multilevel inverter.

**Figure 16.** Output voltage non-optimization 5-level cascaded multilevel inverter Ma=0.68.

**Figure 17.** FFT analysis output voltage non-optimization 5-level inverter Ma=0.68.
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