Three-phase five-level CHB inverter fed induction motor for renewable applications

G. V. V. Nagaraju1, G. Sambasiva Rao2

1 Department of Electrical and Electronics Engineering, Acharya Nagarjuna University, India
2 Department of Electrical and Electronics Engineering, RVR & JC College of Engineering, India

ABSTRACT

This paper presents the three-phase CHB inverter fed induction motor suitable for renewable energy source applications. Normally, all present existing multilevel inverters produce multilevel output, but the number of components required is more, bulk in size, more in cost. Which are more burdens to small capacity renewable sources. These challenges are eliminated in CHB inverter. This CHB mainly consisting of one DC source, one capacitor and eight switches in each phase. To generate a five-level output in phase to ground voltage, it is required to maintain the capacitor voltage (V2) at fifty percent of the DC source voltage (V1). This capacitor voltage is regulated by a sensor less voltage regulating technique. The sensor less voltage regulation works without any sensor devices. We can implement this technique with very less cost compared to other techniques. The sensor less voltage regulation is realized by level-shifted sinusoidal pulse width modulation. The simulation results show a very good dynamic performance. Controller maintains the capacitor voltage at fifty percent of the source voltage irrespective of main source voltage changes and load changes. Inverter generates a five-level wave at the output from line to ground and seven-level wave from line to line with fewer Harmonic. It is implemented in matlab/simulink and showing good dynamic performance.

Keywords: CHB, NPC, Power Quality, Sensor less voltage balancing, Single DC Source

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Corresponding Author:
G. V. V. Nagaraju,
Department of Electrical and Electronics Engineering,
Acharya Nagarjuna University, Guntur, India.
Email: nagaraju006@gmail.com

1. INTRODUCTION

Power demand is rapidly increasing day to day. The entire world searching for new ways to meet this demand by utilizing renewable energy sources. Because the renewable energy sources are pollution-free and eco-friendly. Consequently, an efficient interconnecting medium is required between renewable energy sources and load or grid. The best suitable power electronic device as a medium is multi-level inverters. So many multilevel inverter topologies have been proposed by researchers like NPC, FC and H-Bridge inverters. NPC and CHB are famous topologies [1-5]. NPC is the best topology for three-level configuration with a single DC bus for three-phase applications [6]. It has many drawbacks when increasing the number of levels more than three. Capacitor voltage balancing is the main drawback, unequal voltage distribution among the switches, unequal switching losses distribution among the semiconductor devices, a huge number of switches, capacitors and isolated DC sources are required are also drawbacks of NPC. All these challenges are eliminated in three phase five-level CHB inverter. CHB inverter requires eight switches, one capacitor, and only one DC source per phase [7, 8].
This paper presents the three-phase five-level Cascaded H-Bridge inverter fed three-phase induction motor. Each phase of this inverter control by sensor less voltage regulation. Sensor less voltage regulation is analyzed mathematically and control reference signals are modulated by level-shifted SPWM technique [9-16]. The system is tested in different load conditions using Matlab/simulink and compared with NPC topology.

2. FIVE LEVEL CHB

Five-level inverter is implemented by analyzing typical two-level, three-level, five-level and seven level waves THD results using FFT tool. It is as shown in Table 1. By Comparing two and three-level waveforms, thee level waveform reduces the THD by half naturally. The drop in the THD is similar when migrating from 3-level to 5-level. Such a ratio in THD value is small when going to the upper levels from 5 to 7. It happens because of the fact that five-level wave has been almost near to sine wave shape and THD also low, simultaneously increasing levels requires sensors and controlling devices, which rise in the size and cost. Because of the above merits in five-level inverter research leads in five-level inverters.

| No of voltage levels of waveform | Approximate THD value |
|----------------------------------|-----------------------|
| 2 level                          | 110%                  |
| 3 level                          | 58%                   |
| 5 level                          | 30%                   |
| 7 level                          | 24%                   |

Three-phase five-level Cascaded H-Bbridge inverter fed three-phase induction motor is shown in Figure 1 [17]. It accommodates eight switches, one capacitor and one DC source in each phase. If a DC source of V1 is connected at DC source point, the capacitor voltage V2 must be maintained at fifty percent of V1 by the controller [18, 19]. Hear sensor less voltage regulation is used to maintain the capacitor voltage at the required value. Table 2. shows the all possible switching states to obtain the five-level output [20-25]. It can be observed from Table 2. that the capacitor can be charged or discharged easily by using a switching pattern. During switching state 2 and 6 the capacitor is connected in series with source and load, capacitor charge increases. Similarly, during switching state 3 and 5 capacitors connected in series with a load, capacitor stored energy is supplied to load and capacitor charge reduces. Continuous alternative charging and discharging makes the capacitor voltage balance. These switching sequences are realized by level-shifted sinusoidal pulse width modulation integrated with sensor less voltage balancing [26].

Three Phase Induction Motor

![Figure 1. Three-phase cascaded H-Bridge inverter fed three phase induction motor](image)
3. SENSOR-LESS VOLTAGE REGULATING TECHNIQUE

The DC source voltage ($V_1$) assumed as 2E volts. It is required to maintain the capacitor voltage ($V_2$) at E volts to produce five voltage levels in output. It can be observed from Table 2 that the capacitor can be charged or discharged in a positive half cycle, similarly it can be charged or discharged in the negative half cycle. The capacitor voltage can be maintained constant by maintaining constant charging time and discharging time, in such a way that it should be charged for the first half cycle and discharge for the remaining half cycle. Normally switching state 2 and 3 supplies E volts at output, but switching state 2 charges the capacitor and switching state 3 discharge the capacitor. Hence charging state 2 is used in a positive half cycle. Similarly, in negative half cycle switching state 5 and 6 produce the –E volts, but switching state 5 charges the capacitor and switching state 6 discharge the capacitor, hence charging state 6 is used in a negative half cycle. The charging and discharging are expressed in mathematical form in (1)

$$V_1 = V_2 + V_{out} \Rightarrow \begin{cases} 2E = V_2 + E \\ -2E = V_2 - E \Rightarrow |V_2| = E \end{cases}$$  \hspace{1cm} (1)

Charged and discharged energy in the capacitor is depends on load only, not depends on output frequency or switching frequency. Similarly capacitor size also depends on the load. This self-regulating voltage strategy is mathematically proved with the energy storage relations of the capacitor. The output current and voltage waveforms of a five-level CHB inverter are shown in Figure 2.

Mathematical representation of output current and voltage waveforms at load is shown in (2) and (3)

$$V_2(t) = V_m \sin(\omega t)$$  \hspace{1cm} (2)

$$i_i(t) = I_m \sin(\omega t - \theta)$$  \hspace{1cm} (3)

![Figure 2. Typical output voltage and current of the five-level inverter](image)

Where $V_m$ and $I_m$ are the maximum value of voltage and current respectively, similarly $\theta$ is the phase angle between voltage and current. Output current flowing through capacitor can be written as

$$I = \frac{dq}{dt}$$

$$dU = Vdq = VI dt$$

$$U = \int VIdt$$  \hspace{1cm} (4)

Where $I$ is the current flowing through the capacitor, $V_2$ is the voltage across the capacitor, $q$ is the charge on capacitor plates and $U$ is energy stored in the capacitor. From (3) and (4) the charging energy of the capacitor can be written as follows by considering
\[ U^+ = \int_0^\pi V_C \sin(\omega t - \theta_0) d(\omega t) U^+ \]
\[
= I_m \int_0^\pi \left[ 0 \times \sin(\omega t - \theta_0) d(\omega t) \right] + \int_0^{\alpha_1} E \times \sin(\omega t - \theta_0) d(\omega t) + \int_{\alpha_1}^{\alpha_2} 0 \times \sin(\omega t - \theta_0) d(\omega t) + \int_{\alpha_2}^{\alpha_3} E \times \sin(\omega t - \theta_0) d(\omega t) + \int_{\alpha_3}^{\alpha_4} 0 \times \sin(\omega t - \theta_0) d(\omega t) \bigg] 
= E I_m \left[ \cos(\alpha_1 - \theta_0) - \cos(\alpha_2 - \theta_0) \right] + \cos(\alpha_3 - \theta_0) - \cos(\alpha_4 - \theta_0) \right] 
= E I_m \left[ \cos(\alpha_1 - \theta_0) - \cos(\alpha_2 - \theta_0) \right] + \cos(\alpha_3 - \theta_0) - \cos(\alpha_4 - \theta_0) \right] 
\]
\[ U^- = \int_{-\pi}^{0} V_C I_m \sin(\omega t - \theta_0) d(\omega t) \]
\[
= I_m \int_{-\pi}^{0} \left[ 0 \times \sin(\omega t - \theta_0) d(\omega t) \right] + \int_{-\pi}^{\alpha_1} E \times \sin(\omega t - \theta_0) d(\omega t) + \int_{\alpha_1}^{\alpha_2} 0 \times \sin(\omega t - \theta_0) d(\omega t) + \int_{\alpha_2}^{\alpha_3} E \times \sin(\omega t - \theta_0) d(\omega t) + \int_{\alpha_3}^{\alpha_4} 0 \times \sin(\omega t - \theta_0) d(\omega t) \bigg] 
= E I_m \left[ \cos(\alpha_1 - \theta_0) - \cos(\alpha_2 - \theta_0) \right] + \cos(\alpha_3 - \theta_0) - \cos(\alpha_4 - \theta_0) \right] 
\]

From equation (5) and (6), we can observe that the output voltage is symmetric about positive and negative half. Hence we can write an (7) as

\[
\begin{align*}
\alpha_1 &= \pi + \alpha_1 \\
\alpha_2 &= \pi + \alpha_2 \\
\alpha_3 &= \pi + \alpha_3 \\
\alpha_4 &= \pi + \alpha_4
\end{align*}
\]

The energy stored in a positive half cycle and negative half-cycles are same, but has opposite in polarity

\[ U^+ = -U^- \]

From (8) the energy-charged or discharged by the capacitor is balanced and constant and also it keeps the capacitor output voltage constant irrespective of all conditions. Sensor less voltage control is integrated with level shifted multi carrier PWM modulation. Four carrier signals are used for five-level output, carrier signals and a reference sine wave are shown in Figure 3(a). The reference sine wave is modulated with four vertically shifted triangular signals. This modulation output is mixed with switching states shown in Table 2. Figure 3(b) shows the firing pulse generating algorithm. This algorithm initially fixes the capacitor voltage at the desired value and then produced five voltage levels at the output without any feedback sensor. Table 2 shows the switching positions in various states and capacitor charging/discharging conditions.
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similarly, load current also analyzed in the same way and it showing a THD value of 1.87%. The speed of the motor is shown in Figure 6(a). It reaches to rated value in 0.3 seconds and a sudden load change applied at 0.5 seconds, it created small fluctuation in speed at 0.5 seconds. The overall system has given good dynamic performance under sudden load change condition, voltage change conditions and capacitor voltage balancing also good

Table 3. System parameters used in matlab

| Parameter                          | Value         |
|------------------------------------|---------------|
| \( V_1 \)                          | 440 V         |
| C                                   | 0.015F        |
| Inverter fundamental frequency     | 50 Hz         |
| Squirrel Cage Motor                | 460 V, 50Hz, 3730W |
| Carrier frequency                  | 10 kHz        |
| \( V_{Ref} \) peak to peak         | 3.5 V         |

Figure 4. (a) Three-phase line to line voltage output of inverter with seven levels (b) Phase to ground voltage output

Figure 5. (a) Voltage across capacitor (b) Three-phase load current

Figure 6. (a) Speed of the induction motor (PU), (b) THD spectrum of line voltage
6. CONCLUSION

In this paper, sensor less voltage control was proposed. It is applied to three-phase CHB inverter fed three-phase induction motor. This controller regulates the second source voltage at fifty percent of the first source voltage. However, five levels of voltage in each phase and seven levels of voltage from line to line have been generated in the output of the inverter. It is proved that the sensor less voltage regulator does not require any feedback sensor. Sensor less control is modulated into level-shifted sinusoidal pulse width modulation, which is very simple to implement in applications. This proposed system is best suitable for agricultural water pumping drive fed from a solar energy source. This system requires three voltage sources for three phases.

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**BIOGRAPHIES OF AUTHORS**

G V V Nagaraju received his B.Tech degree in Electrical and Electronics Engineering from JNTU, Hyderabad, India, in 2008 and M.Tech with power system-high voltage from JNTUK, Kakinada, India in 2013. He is pursuing Ph.D in multilevel inverter fed induction motors at Acharya Nagarjuna University, Guntur, India. He is a member of International Association of Engineers.

Dr. G Sambasiva Rao received B.E. degree in Electrical & Electronics Engg., M.E. degree in Power Electronics & Industrial Drives and his doctorate in industrial drives. Since 2006, he has been with R.V.R & J. C. College of engineering, Guntur-522019, India. His research interests are Power Electronics, Electrical Drives, FACTS controllers, Power Quality Improvement.