

Implementation of a New 7-Level H-Bridge Inverter Fed Induction Motor with Low Harmonic Values

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Abstract: A multilevel structure with more than five levels can significantly reduce the harmonic content. The output voltage and power increase with number of levels. Adding a voltage level involves adding a main switching device to each phase. The goal here is to implement the seven level H-bridge inverter with less number of switches. The output of this circuit is fed to the induction motor. Using this scheme, we can control the speed and also reduce the noise and vibration of the induction motor. This research stresses on improving the efficiency of multilevel inverter and quality of output voltage waveform. A new seven level scheme is implemented with only seven switches. The MATLAB simulation is done and hardware is implemented by using IGBT's for the seven switches of seven level inverter.

Key words: IGBT, multilevel inverter, H-bridge, induction motor, vibration, hardware

INTRODUCTION

Multilevel converters can be applied to utility interface systems and motor drives. These converters offer a low output voltage THD and a high efficiency and power factor. There are three types of multilevel converters: diode clamped, flying capacitors and cascaded. The main advantages of multilevel converters include the following, Gobinath *et al.* (2013), Sekhar and Sekhar (2012), Bharath and Satputaley (2013), Kavousi *et al.* (2012), Napoles *et al.* (2013) and Kumar (2012):

- They are suitable for high-voltage and high current applications
- They have higher efficiency since the devices can be switched at a low frequency
- Power factor is close to unity for multilevel inverters used as rectifiers to convert ac to dc
- No Electromagnetic Interference (EMI) problem exists
- No charge unbalance problem results when the converters are in either charge mode (rectification) or drive mode (inversion)

The multilevel converters require balancing the voltage across the series-connected dc bus capacitors. Capacitors tend to overcharge or completely discharge at which condition the multilevel converter reverts to a three-level converter unless an explicit control is devised

to balance the capacitor charge. The voltage-balancing technique must be applied to the capacitor during the operations of the rectifier and the inverter. Thus, the real power flow into a capacitor must be the same as the real power flow out of the capacitor and the net charge on the capacitor over one cycle remains the same (Gobinath *et al.*, 2013; Sekhar and Sekhar, 2012; Bharath and Satputaley 2013; Kavousi *et al.*, 2012; Napoles *et al.*, 2013; Kumar, 2012).

Literature review: In the study of Gobinath *et al.* (2013), two types of methods or topologies have been compared, i.e., cascaded and reduced switches topology. Out of these two, this research uses reduced switches topology. In the study of Maheswari *et al.* (2012), Wanjekeche *et al.* (2012), Kumar *et al.* (2014) and Sathik and Romani (2014), the THD contents of 7-11 and 15 level cascaded multilevel inverters have been discussed. The total harmonic distortion depends on the switching angles for different units of multilevel inverters hence, the switching angles are calculated first by using Newton-Raphson method where some of harmonic components has been eliminated. Using the calculated switching angles, THD analysis is carried out analytically as well as using MATLAB simulation.

The study of Murugesan *et al.* (2012) demonstrates how the reduced harmonic distortion can be obtained for a new topology of multilevel inverters. The new topology has the advantage of its reduced number of devices

compared to conventional cascaded H-bridge multilevel inverter and can be extended for any number of levels. Here, the harmonic reduction is obtained by selection of appropriate switching angles.

The study of Mahendran and Prabhu (2016) deals with the analysis and simulation of the seven level inverter. The percentage total harmonic distortion is calculated for seven level inverter. The functionality verification of seven level inverter is done using MATLAB.

MATERIALS AND METHODS

Reduced switches scheme: The main aim here is to improve the quality of output voltage of the 7-level inverter with lesser number of switches. An important point in this 7-level inverter design is to eliminate lower order harmonics and to generate nearly sinusoidal output voltage waveform. A key issue in the fundamental switching scheme is to properly and carefully determine the switching angles for producing the voltage with fundamental frequency (Kavitha *et al.*, 2014). There are 3 modes of operation of this 7-level inverter. These modes are described in details as Fig. 1 and 2.

Powering mode: This mode of operation occurs when both the load current and voltage have the same polarity. During the positive half cycle when the output voltage is V_{dc} , the path of flow of current consists of the lower supply, D6, Q1, load, Q4 and back to the lower supply. When the output voltage is $2V_{dc}$, the path of flow of current is the lower source, Q5, the upper source, Q1, load, Q4 and back to the lower source. When the output voltage is $3V_{dc}$, the path of flow of current comprises: upper supply, Q1, load, Q4, Q7, lower supply. During the negative half cycle, the switches Q1-Q4 are replaced by the switches Q2-Q3, respectively.

Free-wheeling mode: Free-wheeling mode occurs when one of the main switches is turned off while the load current needs to continue its flow due to the load inductance. This feature is obtained with the help of anti-parallel diodes across the switches and the load circuit is disconnected from the source terminals. In this mode of operation, the positive half cycle current flow comprises: Q1, load and D2 or Q4, load and D3. Whereas, in the negative half cycle, the current flow path includes: Q3, load and D4 or Q2, load and D1 (Bhargava *et al.*, 2014; Atithi and Patel, 2015; Perumal and Nanjudapan, 2011).

Regenerating mode: During this mode of operation, part of the energy stored in the load inductance is returned

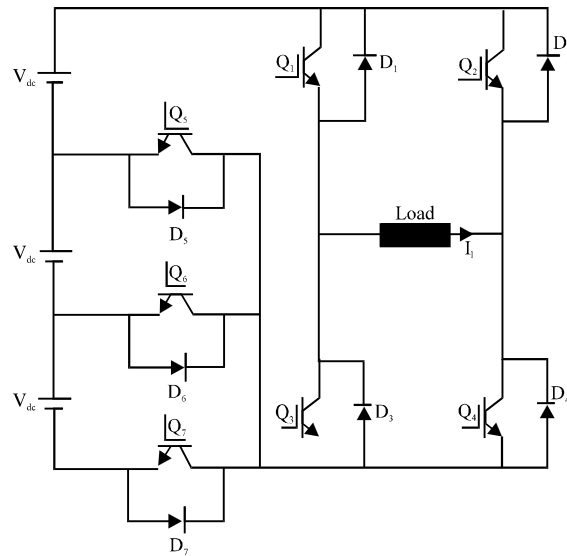


Fig. 1: Power circuit with only 7 switches for 7-level output

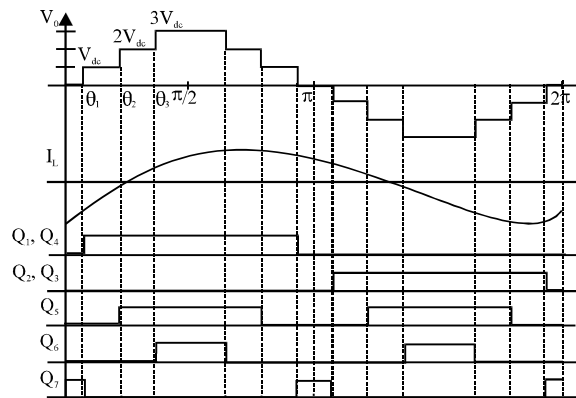


Fig. 2: Waveforms of the 7-level inverter under consideration

back to the source. This occurs during the intervals when the load current is negative during the positive half cycle and vice-versa. During this period, the output voltage is zero.

The positive current flow path consists of: load, D2, Q6, the lower source and D3. While the negative current flow path consists of: load, D1, Q6, the lower source and D4.

Selective harmonic elimination: The Selective Harmonic Elimination Stepped Waveform (SHESW) technique is suitable for a 7-level inverter circuit. Employing this technique along with the multilevel topology, the low Total Harmonic Distortion (THD) output waveform without any filter circuit is possible (Yadav and Bansal, 2014).

Fourier series and harmonics elimination theory: After applying Fourier theory to output voltage waveform of multilevel converters which is odd quarter-wave symmetric, we can find the Fourier expression of multilevel output voltage as given by Eq. 1. If the DC voltages are equal in multilevel converter, the equation for the fundamental frequency switching control method can be given as:

$$V(t) = \sum_{n=1,3,5,\dots}^{\infty} 4V_{dc}/n\pi(\cos(n\theta_1) + \cos(n\theta_2) + \cos(n\theta_3)) \sin(n\omega t) \quad (1)$$

From this Eq. 1, it is seen that the output voltage has no even harmonics because output voltage waveform is odd quarter-wave symmetric. It also can be seen from Eq. 2 that peak values of these odd harmonics are expressed in terms of the switching angles θ_1 , θ_2 and θ_3 . Also, the harmonic equations produced Eq. 2 are transcendental equations. Depending on the harmonic elimination theory, if we want to eliminate the n th harmonic, then:

$$\cos(n\theta_1) + \cos(n\theta_2) + \dots + \cos(n\theta_s) = 0 \quad (2)$$

That means to choose a series of switching angles to let the value of the n th harmonic be zero. Hence, an equation with ‘s’ switching angles will be used to control the ‘s’ different harmonic values. Generally an equation with ‘s’ switching angles is used to determine the fundamental frequency value and to eliminate ‘s-1’ low order harmonics. For an equation with three switching angles, Eq. 2 becomes:

$$V(t) = \sum_{n=1,3,5,\dots}^{\infty} 4V_{dc}/n\pi(\cos(n\theta_1) + \cos(n\theta_2) + \cos(n\theta_3)) \sin(n\omega t) \quad (3)$$

Transcendental equations to solve: Here, we derived harmonic equations for eliminating the 3rd and 5th order harmonics. The resulting harmonic equations are as follows:

$$\cos\theta_1 + \cos\theta_2 + \cos\theta_3 = \pi V_1 / 4V_{dc} \quad (4)$$

$$\cos 3\theta_1 + \cos 3\theta_2 + \cos 3\theta_3 = 0 \quad (5)$$

$$\cos 5\theta_1 + \cos 5\theta_2 + \cos 5\theta_3 = 0 \quad (6)$$

To simplify the expression, Eq. 4 can be written as:

$$\cos\theta_1 + \cos\theta_2 + \cos\theta_3 = m \quad (7)$$

Where:

$$m = \pi V_1 / 4V_{dc} \quad (8)$$

These harmonic Eq. 4-6 are transcendental equations. They are difficult to solve without using some type of numerical iterative technique. Here Newton Raphson method is employed for solving these equations.

Solving the harmonic equations using Newton Raphson method:

To solve the harmonic equations by resultant theory, they must be changed into polynomials. First, we change the variables:

$$x_1 = \cos(\theta_1) \quad (9)$$

$$x_2 = \cos(\theta_2) \quad (10)$$

$$x_3 = \cos(\theta_3) \quad (11)$$

Also, use the following trigonometric identities:

$$\cos 3\theta = 4\cos^3\theta - 3\cos(\theta) \quad (12)$$

$$\cos 5\theta = 5\cos\theta - 20\cos^3\theta + 16\cos^5(\theta) \quad (13)$$

Then, apply them to the transcendental harmonic equations (Eq. 12 and 13) and the following polynomial harmonic equations can be found. For the fundamental frequency harmonic:

$$P_1(x_1, x_2, x_3) = \sum_{n=1}^3 (x_n - m) = 0 \quad (14)$$

For the 3rd harmonic:

$$P_3(x_1, x_2, x_3) = \sum_{n=1}^3 (4x_n^3 - 3x_n) = 0 \quad (15)$$

For the 5th harmonic:

$$P_5(x_1, x_2, x_3) = \sum_{n=1}^3 (5x_n - 20x_n^3 + 16x_n^5) = 0 \quad (16)$$

The polynomial equations can be solved by using the Newton Raphson method. The following are steps for solving the equations. Substitute the initial guesses for variables. Then, form the jacobian matrix with Newton’s formula. Repeat the same steps until the solutions to converge. Thus, the switching angles θ_1 - θ_3 are obtained as follows:

$$\theta_1 = 8.766^\circ, \theta_2 = 28.688^\circ, \theta_3 = 54.939^\circ$$

Figure 2 shows the switching patterns for switches Q1-Q7 become clear. Here, the fundamental frequency switching scheme is employed which drastically reduces the switching losses.

Switching losses are directly proportional to the switching frequency. In this method the switching frequency is less as compared to the other methods and hence the switching losses are less which is a bigger advantage.

Circuit diagram: Circuit diagrams are shown in Fig. 3 and 4.

Components and their functions

PIC microcontroller:

- PIC (Peripheral Interface Controller) microcontrollers are specialized microcontroller chips produced by micro-chips technology in Chandler, Arizona
- The main function of the PIC microcontroller is to govern the operation of embedded systems in motors, vehicles, robots, etc
- PIC16F887 microcontroller is used in the hardware circuit
- The operating frequency of PIC is 0-20 MHz
- The required power supply for the PIC is 2.0-5.0 volts
- There are 35 I/O pins available in PIC

IGBT driver:

- An IGBT driver is a semiconductor chip which is used as a switch or rectifier in power electronic circuit
- Switches are used in order to break or divert a circuit
- There are 7 IGBT drivers used in this implementation
- The input supply and output ranges between 12-24 volts
- IGBT driver consists of opto-coupler and voltage amplifier

IGBT switch:

- It is a 3 terminal power semiconductor device with 4 alternating layers (P-N-P-N) and primarily it is used as an electronic switch
- The rating of each IGBT switch is 12 Amperes and 7 IGBT switches are used
- It switches electric power in many modern appliances
- It is designed to turn on and turn off rapidly

Driver interfacing IC: It is used for microcontroller and driver short circuit protection.

Crystal oscillator: A crystal oscillator is an electronic oscillator circuit which uses the mechanical resonance of

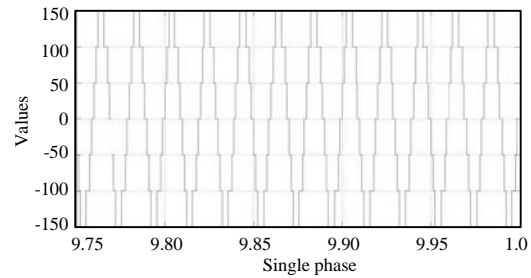


Fig. 3: Output voltage for single phase 7-level inverter

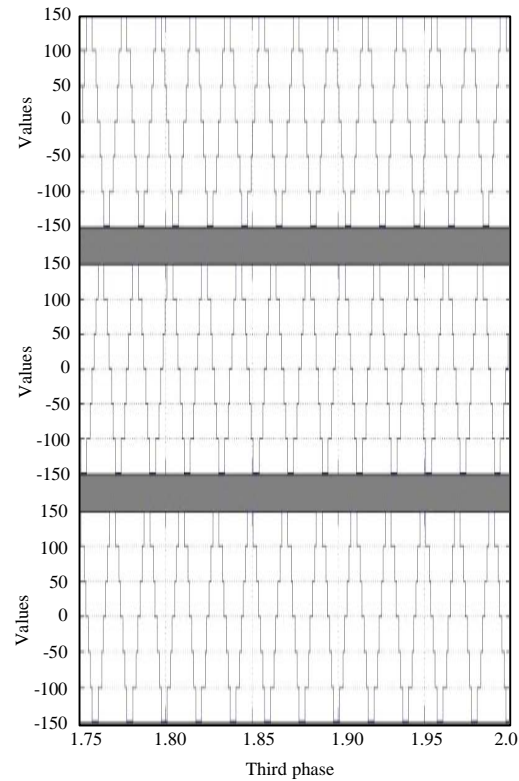


Fig. 4: Phase to ground voltage for 3-phase 7-Level Inverter

vibrating crystal of piezoelectric material to create an electrical signal with a very precise frequency.

Heat sink: It is a substance or device for absorbing unwanted or excessive heat from IGBT and cools it down (Kumar *et al.*, 2014; Murugesan *et al.*, 2012; Mahendran and Prabhu, 2016; Kavitha *et al.*, 2014).

RESULTS AND DISCUSSION

Experimental setup: The last four IGBT's are connected in such a manner so as to form an H-bridge. The output of

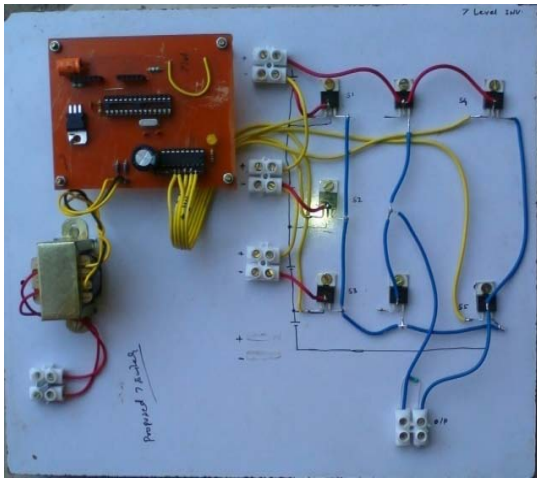


Fig. 5: Experimental setup of the 7-level inverter circuit



Fig. 6: Complete assembly of the experimental setup of 7-level inverter with output waveform

the circuit is taken from this H-bridge and is fed to the load. An induction motor is used as a load which gives a smooth running and an operation free of noise and vibrations (Fig. 5-7).

Applications: There is considerable interest in applying voltage source inverters in high-power applications such as in utility systems for controlled sources of reactive power. In the steady-state operation, an inverter can produce a controlled reactive current and operates as a static Volt-Ampere Reactive (VAR) compensator (STATCOM). Also, these type of inverters can reduce the physical size of the compensator and improve its performance during power system contingencies

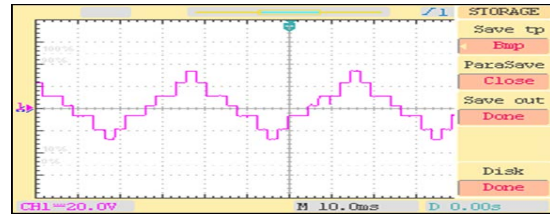


Fig. 7: Output voltage waveform for B phase for the 7-level inverter as seen on Digital Storage Oscilloscope (DSO)

(Perumal and Nanjudapan, 2011; Yadav and Bansal, 2014; Aiswarya *et al.*, 2015). The most common applications of multilevel converters include:

- Reactive power compensation
- Back to back intertie
- Variable speed drives

Other applications include:

- The inverter banks are used in big industries
- They are used in electric traction
- It is used in pump, fan, mills, chemical industries, etc
- It is used in electric and hybrid power trains
- CSI and VSI fed drives are nowadays largely used in the industries for power quality improvement purposes
- They are used in variable speed drive applications

CONCLUSION

- By using the new scheme of multilevel inverter, we are able to reduce the number of switches required
- It reduces the capital cost and complexity
- Though there are 7 switches required, only 3 switching angles θ_1 - θ_3 are sufficient as calculated above for this circuit
- This scheme can be generalized for any number of levels
- 7-level output phase voltage and 9-level output line voltage is obtained with lesser Total Harmonic Distortion (THD) using this new scheme
- Speed control over a substantial range is possible

The proposed scheme has the advantage of its reduced number of switches and harmonics are reduced with THD value of 14.62% at 149 V. The results are well within the specified limits of IEEE standards (Aiswarya *et al.*, 2015).

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