

Development of Active Neutral Point Clamped Multilevel Inverter Fed BLDC Drive Employing FPGA

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Abstract

Multilevel inverters have been popularly used for high power applications. These inverters are preferred for BLDC drive compared to conventional inverters as they reduce the stress across the switches and the spectral quality of the output is improved. This paper presents the implementation of a novel three-phase Active Neutral Point Clamped Multilevel Inverter (ANPCMLI) fed brushless DC motor. The main advantage of BLDC is the presence of electronic commutator. The electronic commutation instants are determined by rotor position which is either by position sensors or by sensorless techniques. In this paper, the commutation logic is implemented using FPGA and it receives hall sensor output from BLDC motor (1kW) and generates the gate pulses which drive the IGBT switches of the proposed multilevel inverter. A model of the ANPCMLI with BLDC drive is simulated in MATLAB and the sensed control is implemented on a FPGA platform. A prototype of three-phase MLI feeding BLDC drive is developed and the simulation results are verified. The performance of proposed inverter is compared with conventional voltage source inverter for BLDC drive. It is found that the torque ripple and harmonics are reduced with the proposed inverter structure.

Keywords: Active Neutral Point Clamped Multilevel Inverter, Brushless DC Motor, Field Programmable Gate Array

1. Introduction

Multilevel inverter is used to synthesize a desired AC voltage from several levels of DC voltages. As the number of levels increases the harmonic content decreases significantly. Diode clamped multilevel inverters has gained more interest because of its advantages over other MLI configurations¹⁻⁷. This paper focuses on a three-phase active neutral point clamped multilevel inverter which solves the unbalanced power loss distribution among the devices that occurs in the conventional diode clamped multilevel inverter⁸⁻¹².

BLDC motor has permanent magnets in rotor assembly to generate steady state magnetic field, due to this it is advantageous compared to induction motors. BLDC motors are used in wide range application from very small motors used in hard disk drives to large motors used in electric vehicles. In conventional DC motors with brushes, field winding is on the stator and armature winding is on the rotor. The DC motor is relatively more expensive and needs maintenance due to the brushes and commutator surface wear. This could be solved by replacing the mechanical switching commutator and brushes using power electronic switches. BLDC motor

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has a rotor and stator, which is connected to a power electronic switching circuit^{13,14}.

A Brushless DC (BLDC) motors, with their trapezoidal electromotive force profile, requires six discrete rotor position information for the inverter operation. These are typically generated by Hall-effect switch sensors placed within the motor. Hall-effect position sensors typically provide the position information needed to synchronize the stator excitation with rotor position in order to produce constant torque. The rotor magnets are used as triggers for the Hall sensor and it receives hall sensor output from BLDC motor (1KW) and generates the gate pulses which drive the IGBT switches of the three-phase active neutral point clamped multilevel inverter. The block diagram is shown in Figure 1. MATLAB/SIMULINK is used for the implementation of the brushless dc motor circuit model and sensed control is implemented using FPGA. The simulation results are verified experimentally.

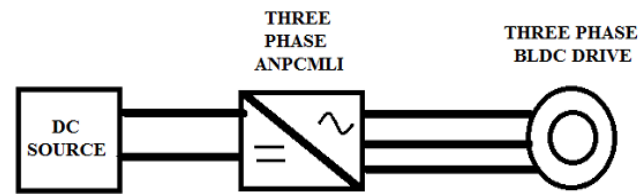


Figure 1. Schematic representation of Active NPCMLI fed BLDC motor load.

2. Mathematical Model of BLDC Motor

Brushless DC motor produces a trapezoidal shape back-EMF, and excited motor current waveform is preferably rectangular-shaped. The stator winding resistances are assumed to be equal. The self inductance and mutual inductances are constant. The rotor-induced currents are neglected. The three phase voltage equation for BLDC can

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s - M & 0 & 0 \\ 0 & L_s - M & 0 \\ 0 & 0 & L_s - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Where

R_s : phase resistance,

v_{an}, v_{bn}, v_{cn} : phase voltages,

L_s : self-inductance,

i_a, i_b, i_c : phase currents,

M : mutual inductance,

e_a, e_b, e_c : phase back-EMFs.

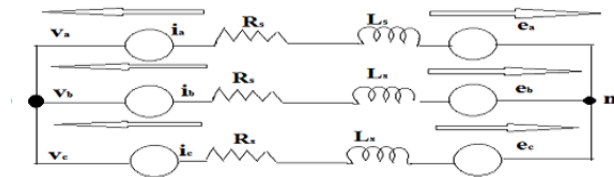


Figure 2. The equivalent circuit for the BLDC motor.

The equivalent circuit for the BLDC motor is shown in Figure 2. Due to the interaction of the stator current and the magnetic field from rotor, the electromagnetic torque of BLDC motor is produced as follows

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \quad (2)$$

Where ω_m is the mechanical speed of the rotor. The motor equation of motion is given by

$$\frac{d\omega_m}{dt} = \frac{T_e - T_L - B\omega_m}{J} \quad (3)$$

Where

T_L : load torque,

B : damping constant,

J : moment of inertia of rotor shaft and load.

For six-step motor control, at each step the instantaneous output power will be deliver from two phases winding connected in series, and the equation is given by

$$P_O = \omega_m \cdot T_e = 2EI \quad (4)$$

Where I is the current amplitude and E is the induced back-EMF. From equations (2) and (4), the output torque can also be expressed as

$$T_e = 2k\phi I = 2k_t I \quad (5)$$

Where k_t is the motor torque constant.

3. Operation of Active Neutral Point Clamped Multilevel Inverter

A three-level active neutral point clamped multilevel inverter is shown in Figure 3 and the output voltage is depicted in Figure 4. An m -level inverter leg requires $2(m-1)$ switching devices and $(m-1)$ $(m-2)$ clamping switches. For a three-level inverter, ($m=3$), it needs four switching devices and two clamping switches per leg as shown in Figure 3.

1. For output voltage of $V_o = V_{dc}$, all the upper side - half switches are turned on, i.e., T_{11} , T_{12} and T_{16} are on.
2. For output voltage of $V_o = V_{dc}/2$, all the lower side - half switches are turned on, i.e., T_{13} , T_{14} and T_{15} are on.
3. For output voltage of $V_o = 0$, only T_{11} , T_{13} , T_{16} are on and T_{12} , T_{14} , T_{15} are off.

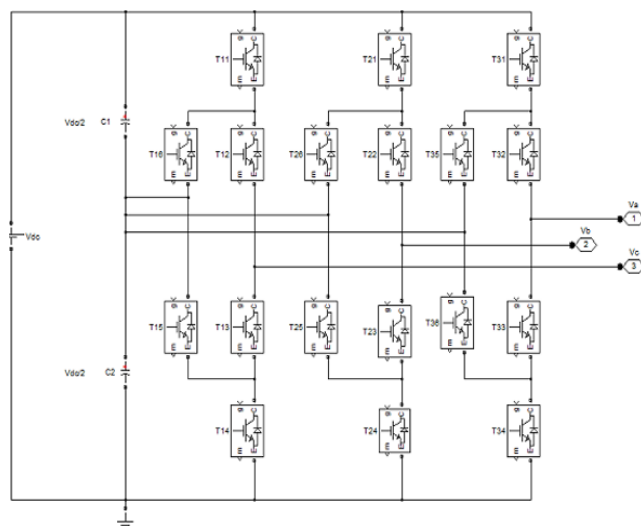


Figure 3. Three Level active neutral point clamped inverter.

Table 1 shows the switching sequence of the proposed MLI. State “1” means the switch is on and state “0” means the switch is off. It should be noticed that there are two complementary switch pairs. These pairs for single leg of the inverter switches are (T_{11}, T_{12}, T_{16}) & (T_{13}, T_{14}, T_{15}) . Thus, if one of the complementary switch pair is turned on, the other of the same pair must be in off condition. Two switches are always turned on at the same time. Figure 4 shows that the output voltage of ANPCMLI respectively.

Table 1. Conduction table for ANPCMLI

Voltage level	T_1	T_2	T_3	T_4	T_5	T_6
V_{dc}	1	1	0	0	0	1
$V_{dc}/2$	0	0	1	1	1	0
Zero	1	0	1	0	0	1

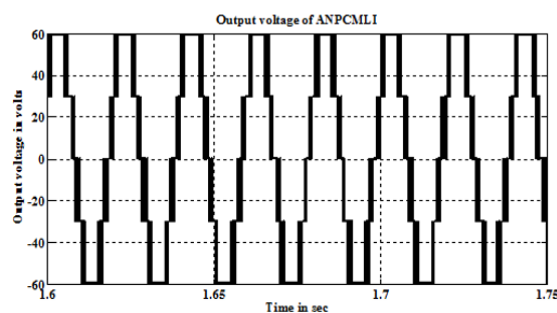


Figure 4. Output voltage waveform of ANPCMLI.

4. Sensored Control of ANPCMLI with Brushless DC Motor

Brushless DC motor has a permanent magnet rotor and a wound field stator and which is connected to a power electronic switching circuit. The brushless DC motor drive system is based on the rotor position, and it is obtained at fixed points typically every 60 electrical degrees for six-step commutations of the phase currents. The brushless DC motor drives have higher efficiency, less maintenance cost, less noise and simple compact construction. In a brushless DC motor, the permanent magnets produce an air gap flux density distribution that is of trapezoidal shape waveform, and result in trapezoidal back-EMF waveforms¹⁸⁻²³.

Brushless DC motors use electric switches to realize current commutation, and thus continuously rotate the motor. These electric switches are usually connected in a three-phase active neutral point clamped multilevel inverter structure for a three-phase BLDC motor. There are two types of control technique for using BLDC drive system. These are position sensor control and position sensor less control but this paper insists on a position sensor control technique. The block diagram is shown in Figure 5.

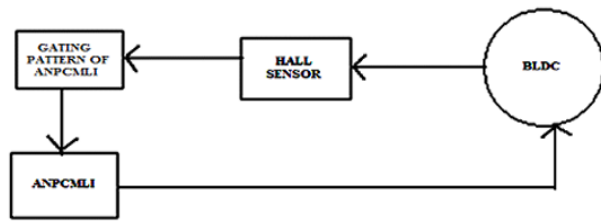


Figure 5. Sensed control of three-phase ANPCMLI fed brushless DC motor.

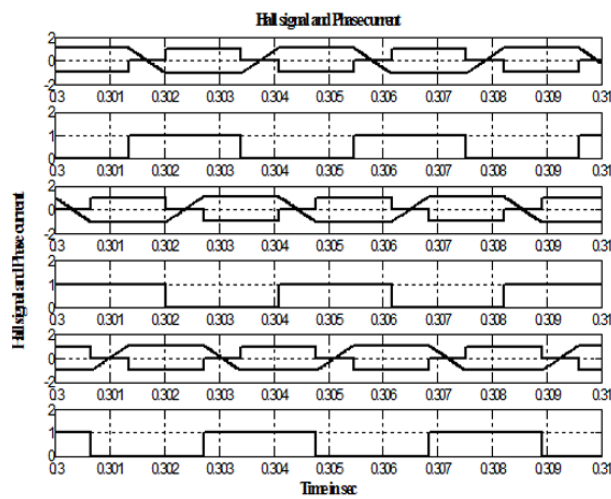


Figure 6. BLDC motor drive along with typical phase current and hall signal.

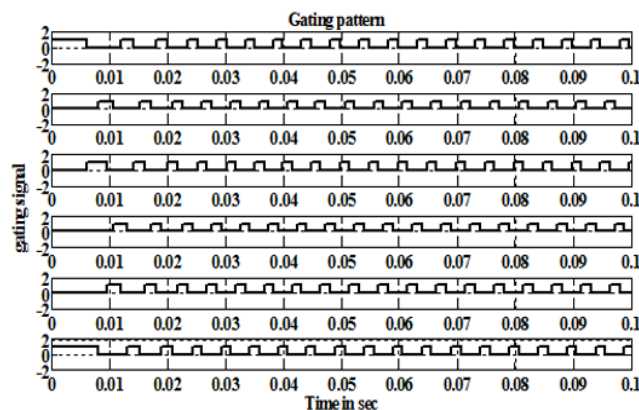


Figure 7. BLDC motor drive along with typical gate signal.

A three- phase BLDC motor requires three Hall sensors to detect the rotor's position based on the physical position of the Hall sensors, there are two types of output: a 60° phase shift and a 120° phase shift. Combining these three Hall sensor signals can determine the exact commutation sequence.

The commutation sequence of a three-phase BLDC motor driver circuit for counter-clockwise rotation. Figure 6 show that the BLDC motor drive along with typical phase current and hall signal. Three Hall sensors A, B, and C are mounted on the stator at 120° intervals, while the three phase windings are in a star formation. For every 60° rotation, one of the Hall sensors changes its state; it takes six steps to complete a whole electrical cycle. In synchronous mode, the phase current switching updates every 60° . However, one signal cycle may not correspond to a complete mechanical revolution. The number of signal cycles to complete a mechanical rotation is determined by the number of rotor pole pairs. Every rotor pole pair requires one signal cycle in one mechanical rotation. So, the number of signal cycles is equal to the rotor pole pairs.

Considering a BLDC motor with three stator phase windings connected in star, the BLDC motor is driven by a three-phase active neutral point clamped multilevel inverter in which the switches are triggered with respect to the rotor position. Figure 7 shows that the gating signals of ANPCMLI.

5. Simulation Results

The Simulink model of the sensed control three phase ANPCMLI with BLDC motor is shown in Figure 8. Table 2 shows simulation parameter for three phase ANPCMLI with BLDC drive.

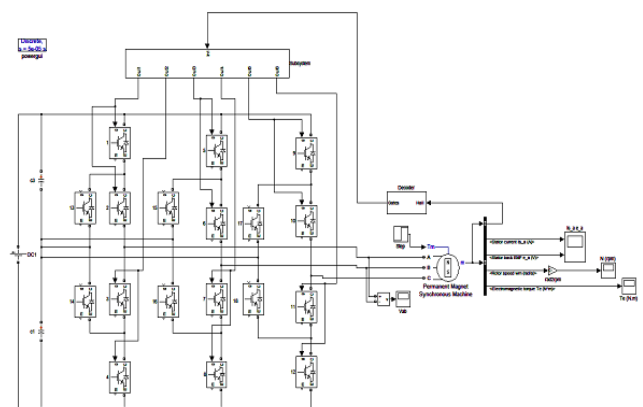
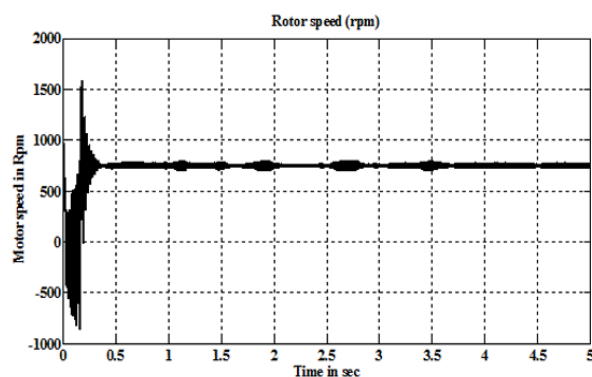
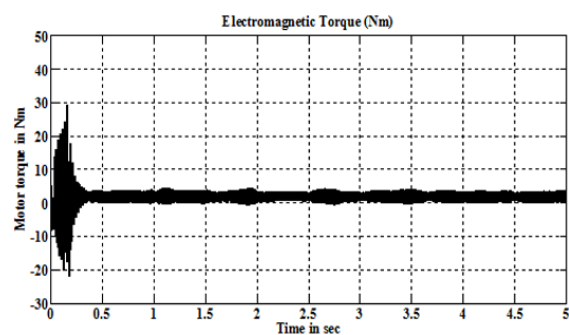
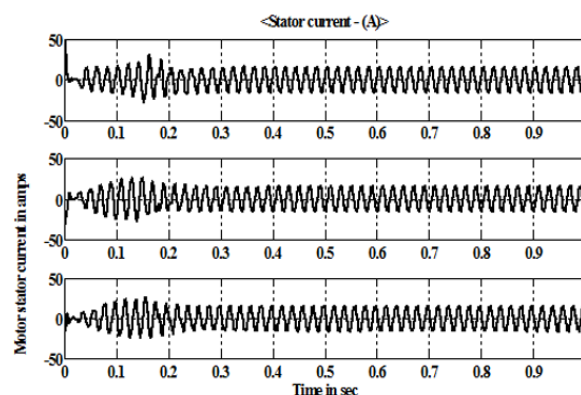
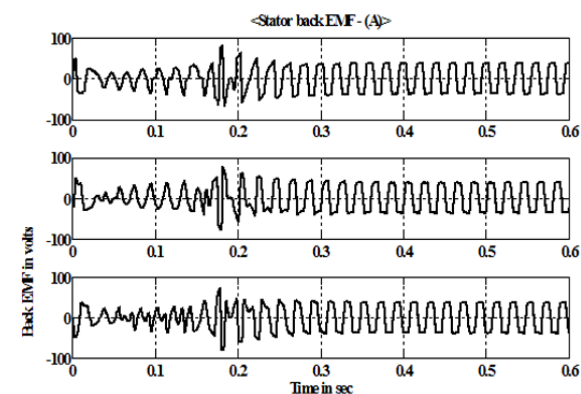
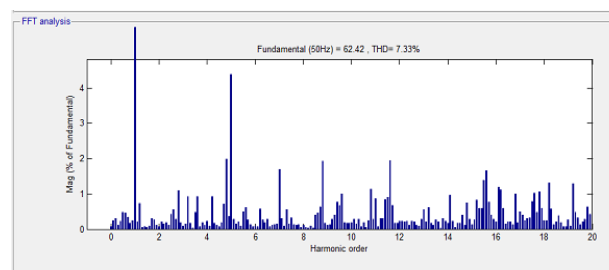
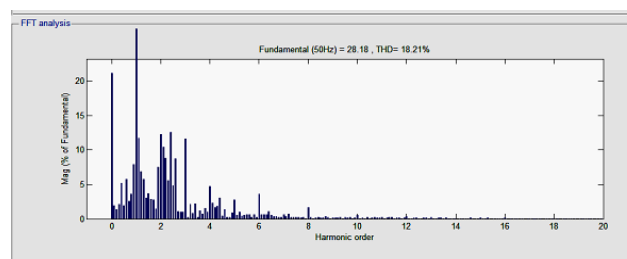


Figure 8. Simulink model of the sensed control three phase ANPCMLI with BLDC drive.

Table 2. Simulation parameters Three-phase ANPCMLI fed BLDC

Simulation parameters	Values
Three phase ANPCMLI inverter	$V_{in} = 60V$
	$P = 1KW,$
BLDC	$V = 130V,$
	$N = 3000 \text{ rpm},$
	$T = 1.4 \text{ N/m}$

The simulated results (rotor speed, electromagnetic torque, stator current and back EMF) of brushless DC motor are shown in Figures 9–12 respectively.

**Figure 9.** Rotor speed for three phase ANPCMLI fed BLDC drive.**Figure 10.** Motor torque for three phase ANPCMLI fed BLDC drive.**Figure 11.** Stator current for three phase ANPCMLI fed BLDC drive.**Figure 12.** Back EMF for three phase ANPCMLI fed BLDC drive.**Figure 13.** Output voltage T.H.D for ANPCMLI.**Figure 14.** Stator current T.H.D for three phase ANPCMLI fed BLDC drive.

Figures 9 & 10 show that the BLDC motor speed is settled 800 Rpm and the BLDC motor torque is about 5 Nm. Figures 11 & 12 show that the BLDC motor stator current is about 15 A and the BLDC motor back emf voltage is about 40 V. Figure 13 shows that the output voltage T.H.D of three phase ANPCMLI with BLDC drive which is about 7.33%. Figure 14 shows that the stator current T.H.D of three phase BLDC drive which is about 18.21%. By employing three phase ANPCMLI fed BLDC the position sensor control technique for the spectral quality of the output voltage, stator current, torque ripple are reduced and improved motor speed compared to the conventional system.

6. Hardware Implementation for Three-Phase ANPCMLI with BLDC Drive System

The hardware prototype of the proposed three phase ANPCMLI is developed using IGBTs as power device, along with isolation and driver circuit etc. The gating pulses were obtained from a Xilinx-FPGA SPARTAN 3E whose input is supplied from the hall sensors. The hardware set-up for three ANPCMLI fed BLDC with FPGA is shown in Figure 15.



Figure 15. Hardware set-up for three phase ANPCMLI fed BLDC with FPGA.

6.1 FPGA Implementation

The hardware prototype presents the development of Xilinx-FPGA SPARTAN 3E as a control circuit for three-phase active neutral point clamped multilevel inverter.

Eighteen I/O lines of SPARTAN 3E are used as PWM output lines for three phase active neutral point clamped multilevel inverter output voltage. VHDL language is used to model the PWM switching strategies and Xilinx ISE 14.1 software is used as a simulation and compiler tool. Generation of PWM pulses is obtained with Xilinx-FPGA SPARTAN 3E board. The VHDL code successfully embedded in FPGA is shown in Figure 16.

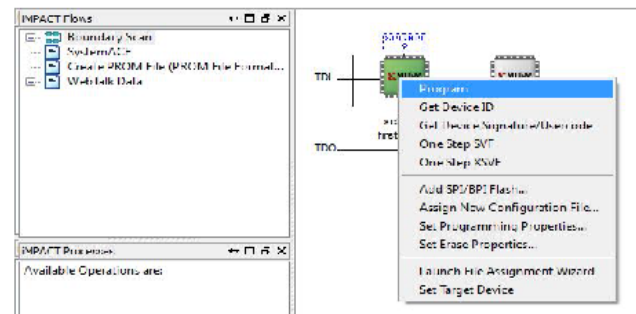


Figure 16. VHDL code successfully embedded in FPGA.

Figures 17-19 show the phase voltage, line to line voltage and the neutral point voltage of three-phase ANPCMLI.

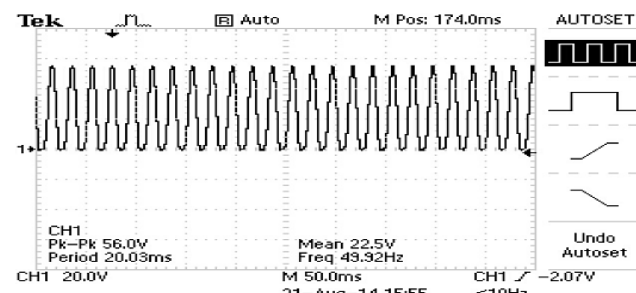


Figure 17. Phase voltage of three Phase ANPCMLI.

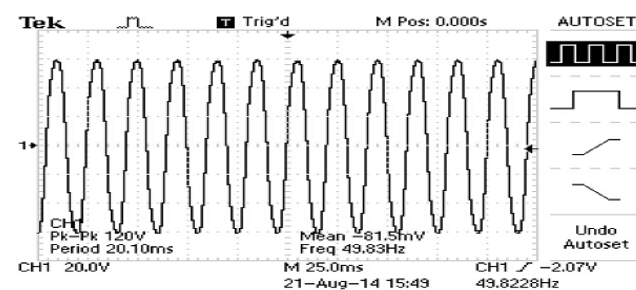


Figure 18. Line to line voltage of three Phase ANPCMLI fed BLDC drive.

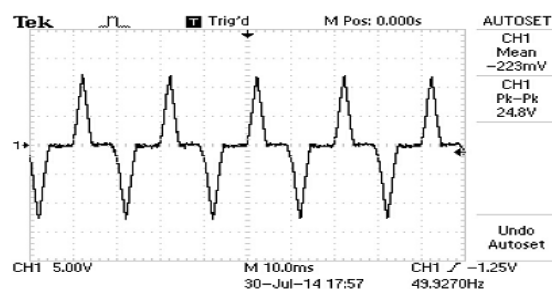


Figure 19. Neutral point voltage of three Phase ANPCMLI with BLDC drive.

Table 3. Comparison between VSI and ANPCMLI

Parameters	ANPCMLI fed	Three phase VSI fed
	BLDC	BLDC
Stator current T.H.D	18.21 %	26.98 %
Output voltage T.H.D	7.33 %	35.67 %
Torque ripple	12.34 %	33.27 %

By employing ANPCMLI fed BLDC drive system, it was found from Table 3 that the harmonics are reduced in the stator current and output voltage then, minimized torque ripple compared to the conventional three-phase inverter fed BLDC drive system.

7. Conclusion

This paper has successfully presented the implementation of ANPCMLI fed BLDC motor using FPGA. By suitably developing the commutation logic in FPGA, appropriate phase and line to line voltage output was obtained for the three-phase active neutral point clamped multilevel inverter fed BLDC drive. Therefore, implementing the control using FPGA for a BLDC motor gives a better output and improved flexibility in design. By employing ANPCMLI for BLDC the spectral quality of the output voltage, stator current & torque ripple are reduced compared to the conventional inverters. The simulation results are verified experimentally. Therefore, the proposed ANPCMLI fed BLDC drive is a suitable choice for electric drive applications.

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