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Comparative Study of Fuzzy Logic Based Speed Control of Multilevel Inverter fed Brushless DC Motor Drive

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ABSTRACT

This paper presents a comparative analysis of speed control of brushless DC motor (BLDC) drive fed with conventional two-level, three and five level diode clamped multilevel inverter (DC-MLI). The performance of the drive system is successfully evaluated using Fuzzy Logic (FL) based speed controller. The control structure of the proposed drive system is described. The speed and torque characteristic of conventional two-level inverter is compared with the three and five-level multilevel inverter (MLI) for various operating conditions. The three and five level diode clamped multilevel inverters are simulated using IGBT's and the mathematical model of BLDC motor has been developed in MATLAB/SIMULINK environment. The simulation results show that the Fuzzy based speed controller eliminate torque ripples and provides fast speed response. The developed Fuzzy Logic model has the ability to learn instantaneously and adapt its own controller parameters based on disturbances with minimum steady state error, overshoot and rise time of the output voltage.

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1. INTRODUCTION

BLDC motor offers many advantages including high efficiency, low maintenance, and absence of mechanical commutator, reduced weight and compact construction. The BLDC motors have been widely used for various industrial applications such as automotive, medical, robotics, etc. based on inherent advantages. They are the most suitable motors in application field with requiring fast dynamic response of speed, because they have high efficiency and can be easily controlled in a wide speed range [1].

Pulse Width Modulated (PWM) voltages are generally employed in Brushless DC motor (BLDC) drive which cause sharp voltage wave fronts (dv/dt) across the motor terminals. In addition, motor damages are there due to the high-voltage change rates (dv/dt) which produce common-mode voltages. High switching frequency increases the gravity of this drawback due to the increased number of times. In each cycle this common-mode voltage is functional [2]–[4]. For variable-speed medium-voltage drive applications it is of big concern where the voltage levels are extremely far above the ground. The expected problem can be resolved by applying variable voltage with lower dv/dt i.e., making use of multilevel inverter (MLI) [5].

In recent years, multilevel inverters have gained much attention in the application areas of medium voltage and high power owing to their various advantages such as lower common mode voltage, lower voltage stress on power switches, lower dv/dt ratio to supply lower harmonic contents in output voltage and current. The multilevel inverters can efficiently work at lower switching frequencies when compared to conventional PWM inverters [6]. The most common MLI topologies classified into three types are diode clamped MLI (DC-MLI), flying capacitor MLI (FC-MLI), and cascaded H-Bridge MLI (CHB-MLI).

In the present scenario of industrial world there is a vast necessity to control the speed of the motor for better production and quality output where rotating machines are used. BLDC motor gives fast and accurate speed response, insensitivity to parameter variations with quick recovery of speed from the disturbance. DC-MLI is used in this paper among various multilevel inverter topologies, because of their simplicity and multiple voltage levels are obtained through a series connection of identical capacitors.

2. PROPOSED TOPOLOGY

2.1. Brushless DC Motor Mathematical Modelling

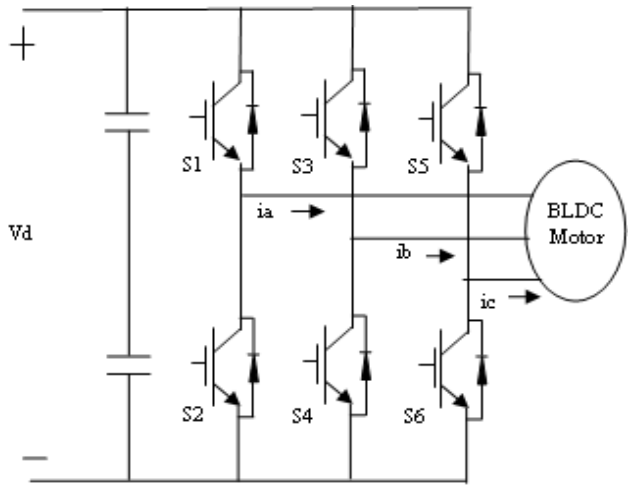

Figure 1. BLDC motor drive system

Figure 1 shows the overall system configuration of the three phase BLDC motor drive. A six switch voltage-source configuration with constant dc-link voltage (V_d) is designed for PWM inverter topology.

The mathematical analysis of a BLDC motor is represented by the following equations. The BLDC motor has three stator windings and permanent magnets on the rotor. Since both the magnet and the stainless steel retaining sleeves have high resistivity, rotor-induced currents can be neglected and no damper windings are modelled. Hence the circuit equations of the three windings in phase variables are:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_a & L_{ab} & L_{ac} \\ L_{ba} & L_b & L_{bc} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

where V_{an} ,V_{bn} and V_{cn} are the phase winding voltage, R_s is the resistance per phase of the stator winding, while i_a, i_b, i_c are the phase current. It has been assumed that the stator resistance of all the windings are equal. Assuming further that there is no change in the rotor reluctances with angle, then

$$L_a = L_b = L_c = L \quad (2)$$

$$L_{ab} = L_{ba} = L_{ac} = L_{ca} = L_{bc} = L_{cb} = M \quad (3)$$

Substituting (2) and (3) in (1) gives the BLDC model as:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = R_s \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (4)$$

But

$$i_a + i_b + i_c = 0 \quad (5)$$

Therefore,

$$Mi_a + Mi_b = -Mi_c \quad (6)$$

Hence,

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = R_s \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (7)$$

The developed electromagnetic torque can be expressed as:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_r} \quad (8)$$

The equation of motion is:

$$J\frac{d\omega_r}{dt} + B\omega_r = T_e - T_l \quad (9)$$

where J is moment of inertia in kg-m^2, B is frictional coefficient in N-ms/rad., T_l is load torque in N-m. The derivative of electrical rotor position is expressed as:

$$\frac{d\theta_r}{dt} = \frac{P}{2}\omega_r \quad (10)$$

where P is number of pole, ω_r is the rotor speed in mechanical rad./sec and θ_r is the electrical rotor position in electrical radian.

2.2. Multilevel Inverter

Multilevel inverters have been attracting in the recent decade for high-power and medium-voltage energy control. The multilevel inverter concept is used to decrease the harmonic distortion in the output waveform without decreasing the inverter power output. Advantages of this multilevel approach include good power quality, good electromagnetic compatibility (EMC), low switching losses and high voltage capability. The term multilevel began with the three-level inverter. The advantages of three-level inverter topology over conventional two-level topology are:

- It can not only generate the output voltages with very low distortion, but also can reduce the dv/dt stresses.
- Multilevel inverters produce smaller common-mode (CM) voltage; therefore, the stress in the bearings of a motor connected to a multilevel motor drive can be reduced.
- Multilevel inverters can draw input current with low distortion.
- These inverters can be operated at both fundamental and high switching frequency pulse width modulation (PWM). Lower switching frequency would yield lower switching losses and thus improving the efficiency.

DC-MLI the most common multilevel inverter topology is used in this paper. In this inverter, diode is used as the clamping device to clamp the dc bus voltage so as to achieve steps in the output voltage. Thus, the voltage stress across the power devices is limited by using diodes which is the main concept of this inverter. The voltage over each capacitor and each switch is V_{dc}. An n level inverter needs (n-1) voltage sources, 2(n-1) switching devices and (n-1)×(n-2) diodes. The quality of the output voltage is improved by increasing the number of voltage levels and the voltage waveform becomes closer to sinusoidal waveform.

Figure 2 shows a three-level DC-MLI consisting of two dc bus capacitors C_1 and C_2. The neutral point 'n' is considered as the output phase voltage reference point for synthesizing the staircase output voltage. There are three switch combinations to synthesize three-level voltages across a and n.

- Voltage level $V_{an}= V_{dc}/2$, turn on the switches S_1 and S_2.
- Voltage level $V_{an}= 0$, turn on the switches S_2 and S_1'.
- Voltage level $V_{an}= -V_{dc}/2$, turn on the switches S_1' and S_2'.

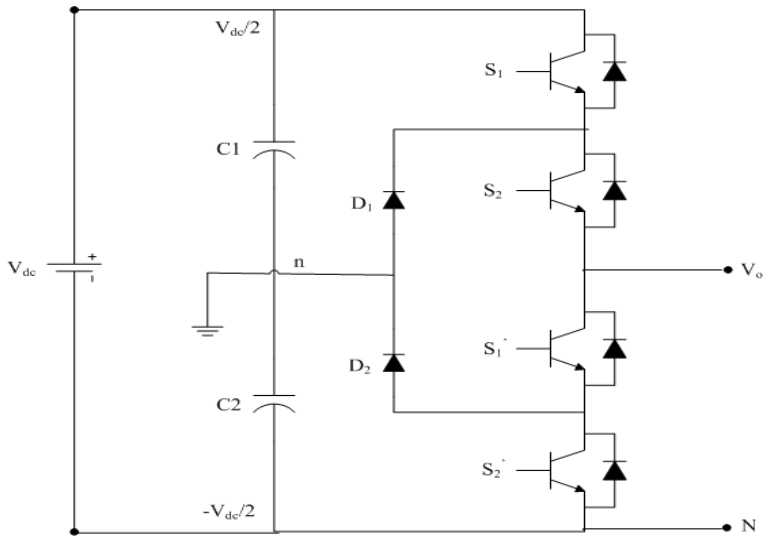

Figure 2. Single phase leg of three level DC-MLI.

A single-phase leg of five-level DC-MLI topology is shown in Figure 3. For dc-bus voltage V_{dc}, the voltage across each capacitor is $V_{dc}/4$ and each device voltage stress will be limited to one capacitor voltage level $V_{dc}/4$ through clamping diodes. To synthesize 5-level output phase voltage, switching sequence is given in Table 1.

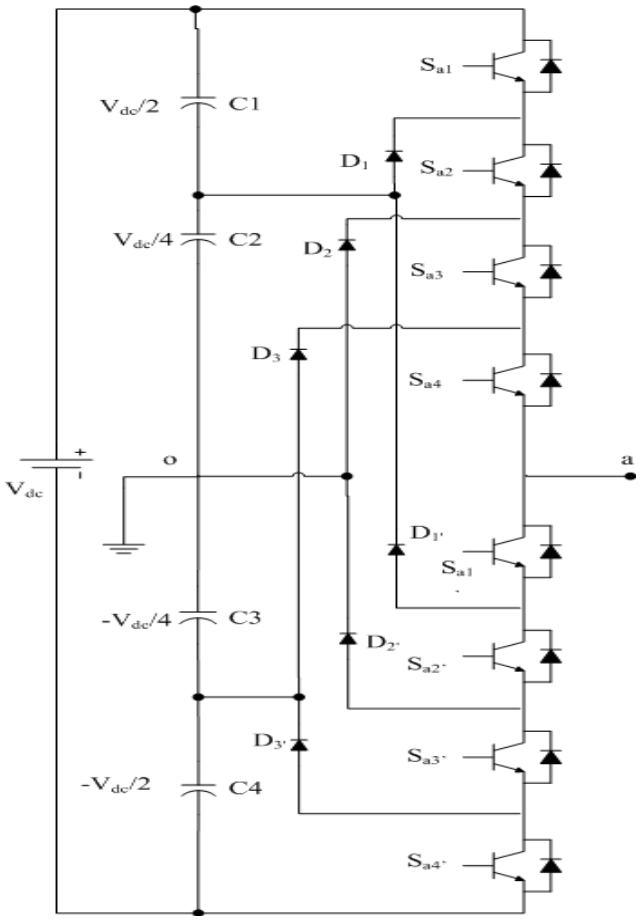

Figure 3. Single phase leg of five level DC-MLI.

Table 1. Voltage levels of five-level DC-MLI and switching state

Voltage=V_{an}	Switching State			
$V_4 = V_{dc}/2$	S_{a1}	S_{a2}	S_{a3}	S_{a4}
$V_3 = V_{dc}/4$	S_{a2}	S_{a3}	S_{a4}	$S_{a4'}$
$V_2 = 0$	S_{a3}	S_{a4}	$S_{a4'}$	$S_{a3'}$
$V_1 = -V_{dc}/4$	S_{a4}	$S_{a4'}$	$S_{a3'}$	$S_{a2'}$
$V_0 = -V_{dc}/2$	$S_{a4'}$	$S_{a3'}$	$S_{a2'}$	S_{a1}

3. CONTROL STRATEGY

Figure 4 explains the control scheme for the BLDC drive system. The BLDC motor drive here is operated in speed and current control mode. The actual speed of the motor is measured which is then compared with the reference speed and this speed error then generates the reference current with the help of reference current generator. This reference current is compared with the actual current in each phase winding and the error is processed by a current controller which generates the pulses for the proper switching of the inverter so that error could be minimized. The PI controller is widely used in industry for speed control due to its ease in design and simple structure. But there will be overshooting, so to reduce overshoot and settling time, fuzzy logic controller is used as speed controller.

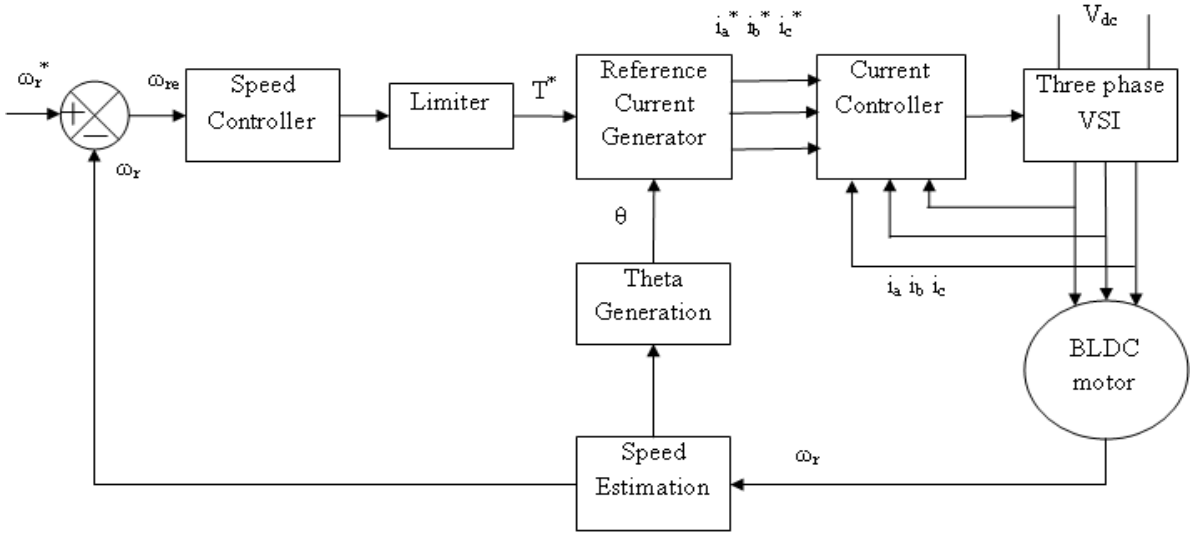

Figure 4. BLDC control scheme

A. Fuzzy Logic Speed Controller

Fuzzy logic control (FLC) is a control algorithm based on a linguistic control strategy which tries to account the human's knowledge about how to control a system without requiring a mathematical model [7, 8]. The basic structure of the fuzzy logic controller system is illustrated in Figure 5.

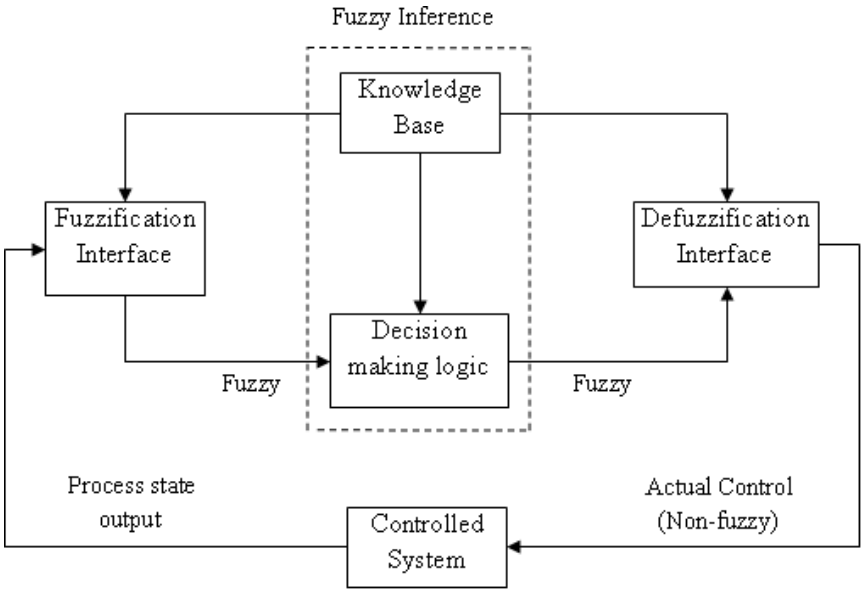

Figure 5. Structure of Fuzzy Logic Controller

Input and output are non-fuzzy values. The basic configuration of FLC is shown in Figure. 6. In this study, Mamdani type of fuzzy logic is used for speed controller. Speed error $\omega_{re}(k)$ and change in speed error $\omega_{cre}(k)$ are the inputs for Fuzzy Logic controller. Speed error is calculated on comparing the reference speed ω_r^* and the actual speed ω_r.

$$\omega_{re}(k) = \omega_r^* - \omega_r \quad (11)$$

$$\omega_{cre}(k) = \omega_{re}(k) - \omega_{re}(k-1) \quad (12)$$

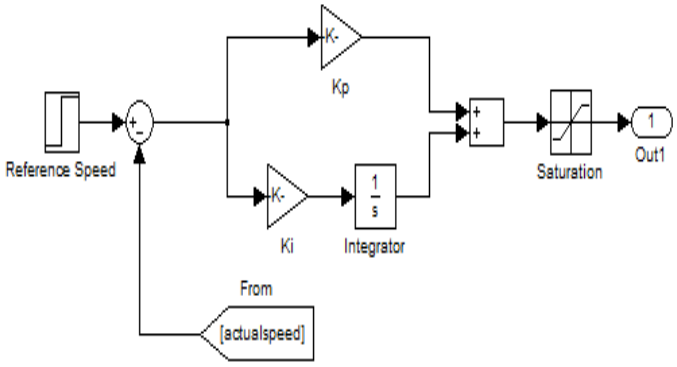

Figure 6. Block diagram of Fuzzy control system

The output of the fuzzy controller u(k) is given by:

$$u(k) = \omega_{re}(k) - \omega_{cre}(k) \quad (13)$$

The fuzzy function approximation includes three stage; fuzzification, inference mechanism and de-fuzzification.

(a) Fuzzification

Fuzzification permits to convert measured crisp inputs into fuzzy linguistic variables output by using membership functions. Each input and output has seven sets associated with seven linguistic labels:

Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Large (PL) as shown in Figure 7. All fuzzy sets are defined on the same universe of discourse [-1, 1].

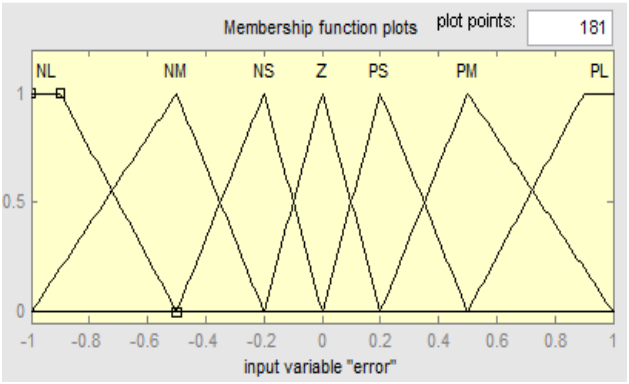

Figure 7. Membership function of ω_{re}, ω_{cre}, u

(b) Fuzzy Inference

The next step is to define the control rules. The value of the fuzzy output is determined using a rule base. A typical rule is described as:

IF (condition 1) AND (condition 2) THEN (conclusion)

The FL controller executes the 49 control rules. The inference method which has been chosen is the Max-Min method that was proposed by Mamdani. Table 2 shows the rule-base for fuzzy logic speed controller. The database contains descriptions of the input and output variables.

(c) Defuzzification

The output of the inference mechanism is fuzzy output variable. The fuzzy function must convert its internal fuzzy output variables into crisp values so that the actual system can use these variables.

Table 2. Rule base for the fuzzy logic speed controller

e / ce	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	Z
NM	NL	NL	NL	NM	NS	Z	PS
NS	NL	NL	NM	NS	Z	PS	PM
Z	NL	NM	NS	Z	PS	PM	PL
PS	NM	NS	Z	PS	PM	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PL	Z	PS	PM	PL	PL	PL	PL

B. Reference Current Generator

The output of the speed controller is reference torque and the reference current is derived from the torque by the expression:

$$T^* = K_T I^* \tag{14}$$

C. Pulse Width Modulation (PWM) Current Controller

PWM controllers are widely used in many applications. The switching frequency is usually kept constant in this technique. PWM control method is based on the principle of comparing a triangular carrier signal of desire switching frequency to the error of the controlled signal. The error signal comes from the sum of the reference signal generated and the negative of the actual motor current value. The comparison of these will result in a control voltage signal that goes to the gates of the voltage source inverter (VSI) to generate the desire output. Its control will thus respond according to the error. If the error signal is greater

than the triangular carrier signal, the inverter legs upper switch will be held on. When the error signal is less than the triangular signal, the inverter legs lower switch will be held on. Thus the PWM signals are generated. The inverter leg is forced to switch at the frequency of the triangular wave and produces an output voltage proportional to the current error command. The controlled output current consists of a regeneration of the reference currents with a high-frequency PWM ripple superimposed on it.

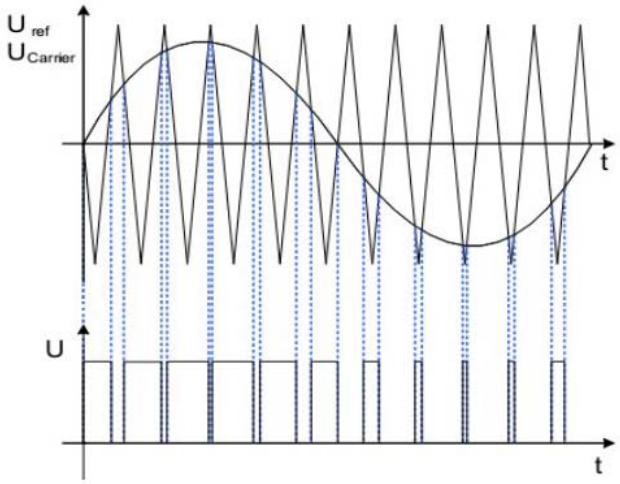

Figure 8. PWM switching signals.

The control principle of the sinusoidal PWM is to use several triangular carrier signals keeping only one modulating sinusoidal signal. For a m-level inverter, (m-1) triangular carriers are needed. The main parameters of the modulation process are:

- The frequency ratio k= f_c/f_m, where f_c is the frequency of the carrier signal and f_m is the frequency of the modulating signal.
- The modulation index

$$M = \frac{\text{Amplitude of reference signal}}{\text{Amplitude of carrier signal}}$$

4. RESULTS

Simulation of BLDC motor is carried out using MATLAB/SIMULINK. The parameters of the BLDC motor are given in Table 3. The simulation is done to compare the performance of two, three and five-level multilevel inverter fed BLDC motor when Fuzzy Logic speed controller is used. The BLDC motor was simulated under the following different conditions. The motor speed and electromagnetic torque is observed for each case.

Table 3. Simulation parameters of BLDC motor

PARAMETERS	VALUES
Pole Pairs	4
Stator Resistance per phase	1.5Ω
Stator Inductance per phase	8.5mH
Torque Constant(Nm/Apeak)	1.4
Voltage Constant(VpeakL-L/k-rpm)	146.077
Moment of Inertia	0.008kgm^2
Friction Coefficient	0.001Nm-s

CASE I: At dynamic load condition

A load of 2 N-m is applied to motor at t = 0.1 sec. From the speed and torque response shown in Figure 9 and Figure 10, it is observed that as the voltage level goes on increasing the ripples in the torque decreases and there is a fast speed response.

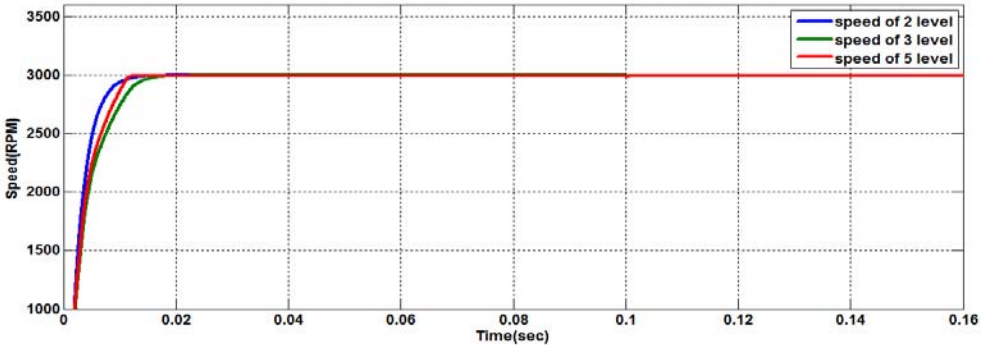

Figure 9. Comparison of speed response of 2, 3 and 5-level inverter at dynamic load condition.

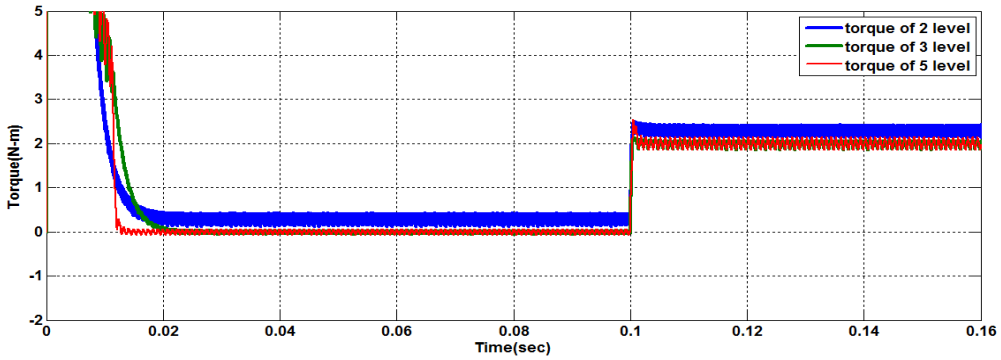

Figure 10. Comparison of torque response of 2, 3 and 5-level inverter at dynamic load condition.

CASE II: With change in reference speed condition.

When there is change in reference speed from 3000 rpm to 2500 rpm at 0.1 sec, there is smooth change in speed response and torque when FLC is used as shown in Figure 11 and Figure 12.

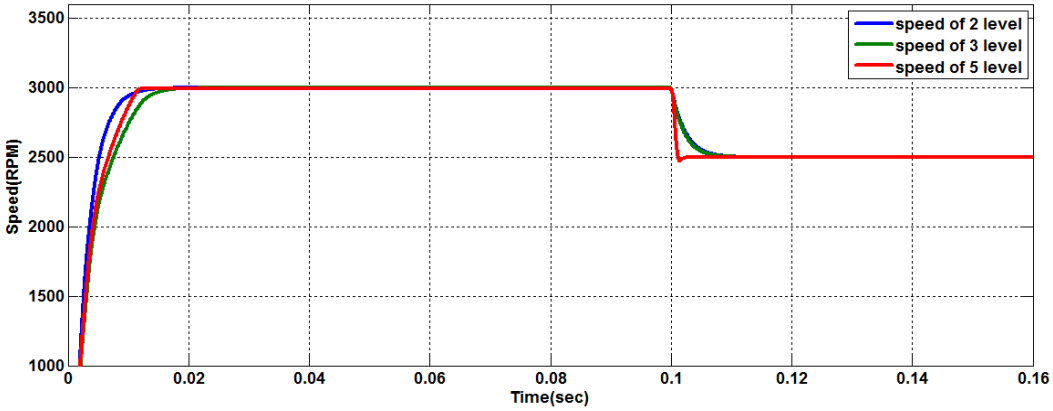

Figure 11. Comparison of speed response of 2, 3 and 5-level inverter with change in reference speed condition.

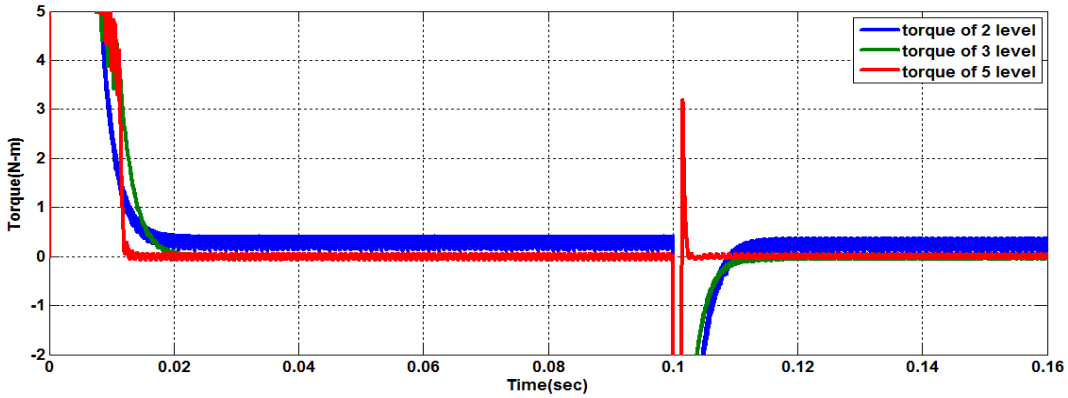

Figure 12. Comparison of torque response of 2, 3 and 5-level inverter with change in reference speed condition.

Below Figure 13 and Figure 14 show the line to line voltage of three phase three and five-level DC-MLI fed BLDC motor using fuzzy logic speed controller at load condition. At t = 0.1 sec, a load of 2 N-m is applied to the motor. An input voltage of V_{dc} = 500 V is applied to the inverter. From the voltage waveform it is observed that the staircase output voltage is synthesized.

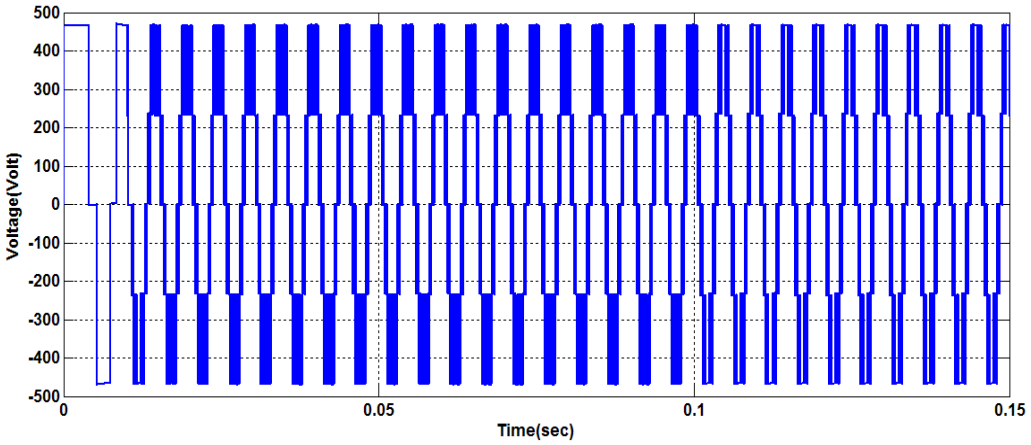

Figure 13. Three phase 3-level multilevel inverter voltage waveform.

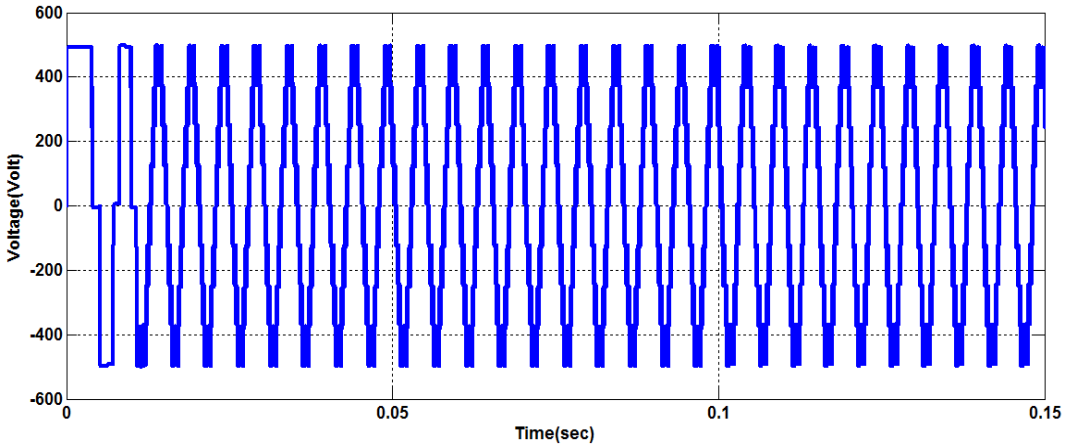

Figure 14. Three phase 5-level multilevel inverter voltage waveform.

5. CONCLUSION

In this paper, a comparative study of Fuzzy Logic based speed control of BLDC motor drive fed with conventional two-level, three and five-level diode clamped multilevel inverter is done. From the simulation results we can conclude that as the voltage level increases the performance characteristics of the BLDC drive has been improved and the harmonics in the output voltages and currents has been reduced. Also the speed and torque characteristics of BLDC drive are having good transient and steady state response. The advantages of the Fuzzy Logic controller are that it reduces computational time, learns faster and produces lower errors than other method.

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Satyadharma Bharti (member IEEE) has received degree of B.E. in Electrical Engineering from Govt. Engg. College Jabalpur (RDVV Jabalpur) in 1990. He completed his Master of Technology (I&C) from B.I.T. Durg (Pt. Ravishankar Shukla University, Raipur) in 2007. He is pursuing Ph.D. from CSVTU, Bhilai, India. Currently he is Associate Professor in the Deptt. of Electrical Engg. Rungta College of Engineering & Technology, Bhilai, India. His research interests include High voltage Engineering, Electrical Machines, Power system, Power Electronics.