Review on Impact of Controlling Techniques on the Performance of BLDC Motor

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Abstract— This paper presents a comparative study on speed control of BLDC motor using various controlling techniques. Speed control of BLDC motor can be achieved by estimating different parameters such as rotor speed, position and phase-to-phase BEMF and torque through DTC, P, PI& PID control, Fuzzy logic PI control, CCSVM based control and sliding mode control. Now a day the demand of BLDC motor increases due to their high efficiency, simpler structure, better controllability and large torque to inertia ratio compared to BLAC motors. In many applications, obtaining a low-frequency ripple-free torque and instantaneous torque and even flux control are of primary concern for BLDC motors with non sinusoidal back-EMF. It is very much essential to propose a study to know about the effectiveness of the control methods employed for BLDC motor drives. Hence a theoretical study is developed and the results obtained by simulation are presented to show the effectiveness of the various methods.

Key words: bldc motor, dtc, p, pi, pid, fuzzy logic

I. INTRODUCTION

In conventional DC motors with brushes, the field winding is on the stator and armature winding is on the rotor. The motor is expensive and needs maintenance because of the brushes, the accumulation of the brush debris and dust, and commutator surface wear. Moreover, in certain hazardous locations, the application of DC brushed motors is limited because of the arcing. This could be solved by replacing the mechanical switching components (commutator and brushes) with electronic semiconductor switches. Brushless DC (BLDC) motor has a permanent magnet rotor and a wound field stator connected to a power electronic switching circuit. BLDC motor drives have high efficiency, low maintenance and long life, low noise, control simplicity, low weight, and compact construction. BLDC control drive systems are based on the feedback of rotor position obtained at fixed points typically every 60 electrical degrees for six-step commutation of the phase currents [1]. Brushless motors can be classified as either trapezoidal or sinusoidal based on the shape of their back-EMF.

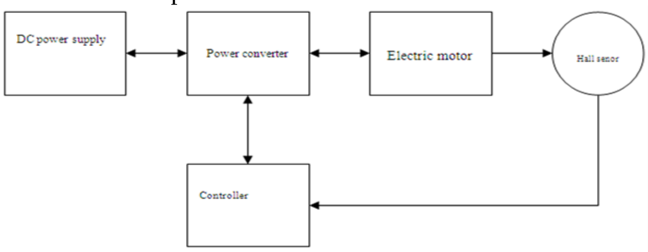

Fig.1: BLDC motor Drive components

In BLDC motors with trapezoidal back-EMFs, the permanent magnets produce a trapezoidal air gap flux density distribution. These motors have higher torque and larger torque ripples compared with motors that have sinusoidal shaped back-EMF. They are also cheaper and used for general applications [2]. The BLDC drive system consists of BLDC motor, power electronics converter, sensor, and controller as shown in Fig. 1.

II. DIRECT TORQUE CONTROL

Most methods are complicated and do not consider the stator flux linkage control, therefore, possible high-speed operations are not feasible. This method does not require pulse width modulation and proportional plus integral regulators and also permits the regulation of varying signals. Furthermore, to eliminate the low-frequency torque oscillations, two actual and easily available back EMF constants (*kba* and *kca*) according to electrical rotor position are obtained offline and converted to the *dq0* frame equivalents using park transformation. sensorless three-phase conduction DTC of BLDC motor drive scheme are verified through simulations and experimental results.

Electromagnetic torque is calculated from the product of the instantaneous back EMF and current both in two-phase and in the commutation period. Then, the prestored phase back EMF values are obtained using mid precision position sensor. As a result, torque pulsations due to the commutation are reduced. This method provides advantages of the classical DTC such as fast torque response compared to vector control, simplicity (no PWM strategies, PI controllers, and inverse Park and inverse Clarke transformations), and a position-sensorless drive. Control the stator flux indirectly using *d*-axis current. Therefore, flux weakening operation is possible. Coordinate transformations are done by the new Park transformation[5].Since the balanced systems in dq-axes reference frame do not require a zero sequence term, first Clarke transformation from the balanced three-phase quantities is derived and, then the Park transformation forming a 2 × 2 matrix instead of a 2 × 3 matrix for three-phase systems can be obtained. Using some algebraic manipulations, the original Clarke transformation forming a 2 × 3 matrix excluding the zero sequence can be simplified to a 2 × 2 matrix.

A. Mathematical Model Of BLDC Motor

Three phase star connected BLDC motor can be described by the following equations,

$$V_{ab} = R_s(i_a - i_b) + L_s\frac{d}{dt}(i_a - i_b) + e_a - e_b \quad (1)$$

$$V_{bc} = R_s(i_b - i_c) + L_s\frac{d}{dt}(i_b - i_c) + e_b - e_c \quad (2)$$

$$V_{ca} = R_s(i_c - i_a) + L_s\frac{d}{dt}(i_c - i_a) + e_c - e_a \quad (3)$$

The equation of the motion can be expressed as:

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \quad (4)$$

Where *v* , *i* and *e* denote the phase-to-phase voltage, phase current and BEMFrespectively in the three phase a, b and c. Rs and Ls denote the resistance and inductance of stator winding. Te electromagnetic generated torque, TL is the load torque, B is the friction coefficient, J is the polar moment of inertia and *m* is the angular velocity of rotor.

B. Sensorless DTC Of BLDC Motor Drive

Indirect torque control method of BLDC motor explained is extended to a direct torque and indirect flux control technique, which is suitable for sensorless and flux weakening operations. The proposed method transforms *abc* frame quantities to *dq* frame ones using the new 2 × 2 Park transformation matrix. in the proposed balanced system only two electrical rotor position dependant back EMF constants (*kd* (θre) and *kq* (θre)) are required in the torque estimation algorithm. this DTC method differs by its torque estimation and voltage vector selection table which is similar to the one used for DTC of PMSM drives explained.

$$\varphi^r_{qs=}L_s i^T_{ds} + \varphi'_r \sum_{n=1}^{\infty}(K_{6n-1} + K_{6n+1)}\sin(6_n\theta_r) \quad (5)$$

$$\varphi^r_{ds=}L_s i^T_{qs} + \varphi'_r \sum_{n=1}^{\infty}(K_{6n-1} + K_{6n+1)}\cos(6_n\theta_r) + \varphi'_r (6)$$

Because of the rotor position dependant terms in the *dq* frame stator flux linkages and inductances, conventional torque estimation in stator reference frame used for DTC of sinusoidal ac motors is no longer valid for BLDC motor, therefore, a new torque estimation algorithm is derived in *dq0* frame consisting of actual *dq0*-axes back EMF constants and currents. Instead of the actual back EMF waveforms, Fourier approximation of the back EMFs could have been adopted in torque estimation, but the results would not truly represent the reality and more complex computations are required [5].

This method provides advantages of the classical DTC such as fast torque response compared to vector control, simplicity and a Position sensorless drive. It is shown that the BLDC motor could also operate in the flux-weakening region by properly selecting the *d*-axis current reference in the proposed DTC scheme.

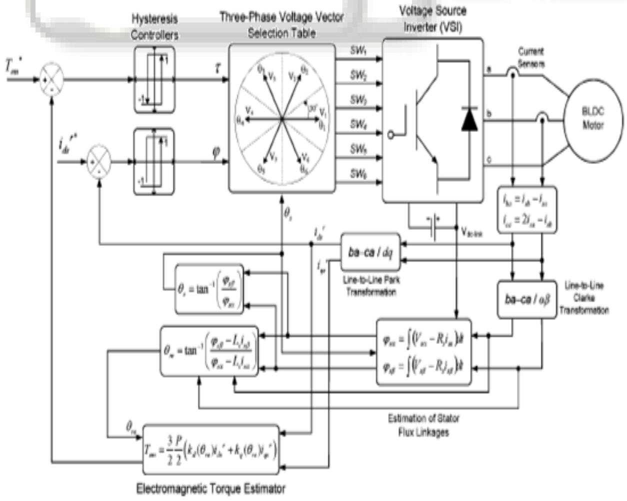

Fig. 2: Direct Torque Control of BLDC Drive

First, practically available actual two line-to-line back EMF constants (*kba* and *kca*) versus electrical rotor position are obtained using generator test and converted to the *dq* frame equivalents using the new Park transformation in which only two input variables are required. Then, they are used in the torque estimation algorithm.

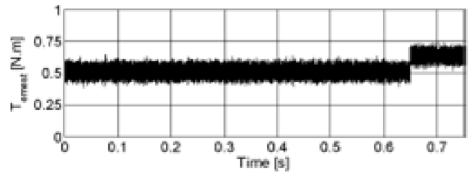

Fig. 3: Estimated electromagnetic torque, (bottom) error between reference and estimated electromagnetic torque.

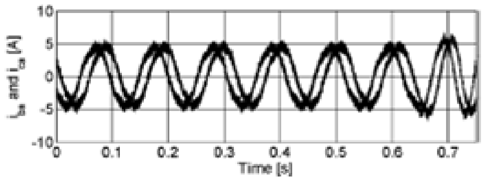

Fig. 4: q-axis stator current and *d*-axis stator current

position-sensorless three-phase conduction DTC scheme for BLDC motor drives that is similar to the conventional DTC used for sinusoidal ac motors where both torque and flux are controlled, simultaneously.

III. SLIDING MODE OBSERVER

An inverter must supply a rectangular current waveform whose magnitude is proportional to the motor's shaft torque. The BEMF wave form of a BLDC motor is trapezoidal shape due to the concentrated winding. In this paper BLDC with 120º conduction mode is proposed, that means only two-phase conduct at any instant of time. BLDC motor fed by two-phase conduction has higher power/weight and torque/current ratios. Ideally a BLDC motor supplied with rectangular 120º elec. Phase currents produce a trapezoidal BEMF waveform whose amplitude is constant over >120º elec. will result a ripple free torque. However, in a practical BLDC drive torque pulsation arise due to the deviation of BEMF waveform from the ideal. In DTC scheme, the torque command obtained from two level hysteresis controller by comparing the estimated electromagnetic torque with their reference value which is obtained from speed error. For the control, voltage vector is selected from a look-up table which depends on rotor flux vector position and the torque error to reduce switching frequency and torque ripple in commutation region. Hall effect sensors are usually used as position sensors to know the position of commutation points [2]. Normally these sensors are mounted on the stator with 120º apart. These sensors increase the cost, size and weight of the motor and reduce the reliability of the total system. To overcome these problems, the sensorless method has been developed to estimate the position and velocity of the rotor from the estimate of phase-to-phase BEMF using sliding mode observer. Sliding mode observer is a non-linear high gain observer has the ability to bring co-ordinates of the estimator error dynamics to zero in finite time. Under two-phase conduction, the amplitude of stator flux linkage cannot easily be controlled due to sharp changes and the curved shape of the flux vector locus between two consecutive commutation points. Transforming the state equation of BLDC motor in α-β stationary reference frame can be written as

$$V_{s\alpha} = R_s i_{s\propto} + L_s \frac{di_{s\propto}}{dt} + e_{\propto} \quad (7)$$

$$V_{s\beta} = R_s i_{s\beta} + L_s \frac{di_{s\beta}}{dt} + e_{\beta'} \quad (8)$$

Electromagnetic torque for DTC can be expressed as:

$$T_e = \frac{3p}{4}\left[\frac{d\Psi_{r\alpha}}{d\theta_e} i_{s\alpha} + \frac{d\Psi_{r\beta}}{d\theta_e} i_{s\beta}\right] \quad (9)$$

Then the electromagnetic torque can be written as,

$$T_e = \frac{3p}{4}\left[\frac{e_\alpha}{\omega_e} i_{s\alpha} + \frac{e_\beta}{\omega_e} i_{s\beta}\right] \quad (10)$$

Rotor angular velocity for the electromagnetic torque calculation can be obtained from the estimate of sliding mode observer.

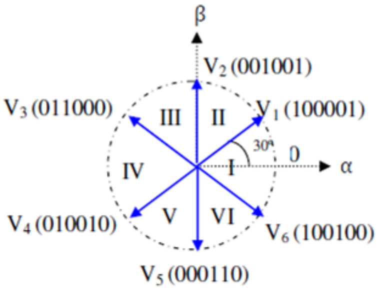

Fig. Two-phase voltage space vectors and sectors

For the direct torque control, a switching pattern of inverter is selected according to the output of hysteresis controller and the flux vector position[2].

The six voltage vectors and the sectors. voltage vector, Vi for DTC scheme is selected accordingly. τ denotes the output of hysteresis controller and the sector is denoted as θr. If the reference torque greater than the actual torque, within the hysteresis band limit, the output of the hysteresis controller is defined as τ=1 otherwise τ= -1, out of the six voltage vector, the proper voltage vector for inverter is selected based on the switching table.

A. Rotor Flux Observer

Using rotor flux observer, the rotor flux

$$\Psi_{r\alpha} = -L_s i_{s\alpha} + \int (V_{s\alpha} - R_s i_{s\alpha}) dt \quad (11)$$

$$\Psi_{r\beta} = -L_s i_{s\beta} + \int (V_{s\beta} - R_s i_{s\beta}) dt \quad (12)$$

$$\theta_r = tan^{-1}\left(\frac{\Psi_{r\beta}}{\Psi_{r\alpha}}\right) \quad (13)$$

B. Sliding Mode Observer

Sliding mode observer is used for the phase-to-phase BEMF estimation accurately. Sliding mode observer is proposed as:

$$\frac{di_{s\alpha}}{dt} = -\frac{R_s}{L_s} i_{s\alpha} - \frac{e_\alpha}{L_s} + \frac{V_{s\alpha}}{L_s} + K_{11} sgn(i_{s\alpha}) \quad (14)$$

$$\frac{di_{s\beta}}{dt} = -\frac{R_s}{L_s} i_{s\beta} - \frac{e_\beta}{L_s} + \frac{V_{s\beta}}{L_s} + K_{22} sgn(i_{s\beta}) \quad (15)$$

$$\frac{de_\alpha}{dt} = K_{33} sgn(i_{s\alpha}) \quad (16)$$

$$\frac{de_\beta}{dt} = K_{33} sgn(i_{s\beta}) \quad (17)$$

The sliding surface S is defined as the error between the actual and estimated currents [2].

$$S = [S_\alpha, S_\beta]^T \quad (18)$$

When the estimation error trajectories reach the sliding surface i.e., S=0, the observed currents will converge to actual. V To find the observer gain, consider the positive definite Lyapunov function as:

$$V(i_s) = {}^1/_2\, (i_{s\alpha}^2 + i_{s\beta}^2) \quad (19)$$

In order to ensure the convergence of the observer, the gains should satisfy the following conditions,

$$K_{11} > \frac{1}{L_s} \mid e_\alpha \mid_{max} \; and \; K_{22} > \frac{1}{L_s} \mid e_\beta \mid_{max}$$

$$\frac{K_{31}}{K_{11}} < 0 \; and \; \frac{K_{42}}{K_{22}} < 0$$

Here KΣ1= K11= K22 ανδ KΣ2= K31= K42

B. Rotor Position And Speed Estimation

The detection of the six rotor positions (θr) for the proper commutation of a bldc motor can be easily determined from the estimated back-emfs in the α-β stationary reference frame. The estimated rotor position as follows,

$$\theta_r = tan^{-1}\left(\frac{e_\beta}{e_\alpha}\right) \quad (20)$$

$$\omega_r = \frac{E_{\max(phase-to-phase)}}{2K_e}$$

The overall block diagram of sensorless direct torque control of BLDC drive was simulated by MATLAB/Simulink.

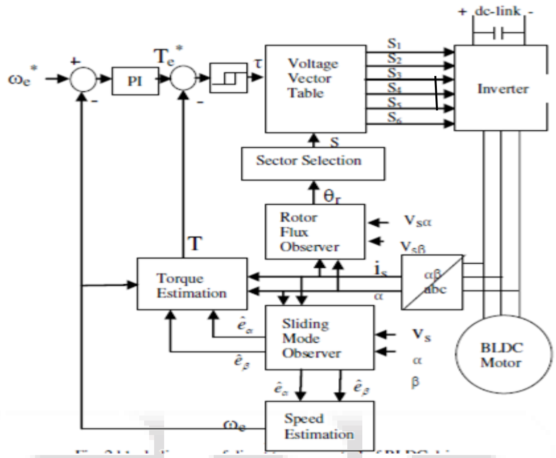

Fig. 5: Sensorless Direct Torque Control of BLDC Drive

The actual and estimated stationary reference frame phase-to-phase back-EMF, Eab using saturation functions are respectively. In order to reduce the chattering, instead of saturation is given.

Then it is observed that the chattering is reduced to great extent. the actual and estimated rotor position using SMO with saturation functions respectively. the estimated rotor position shows the effect of chattering problem. When the saturation function used as a control signal in SMO, the effect of chattering considerably reduced.

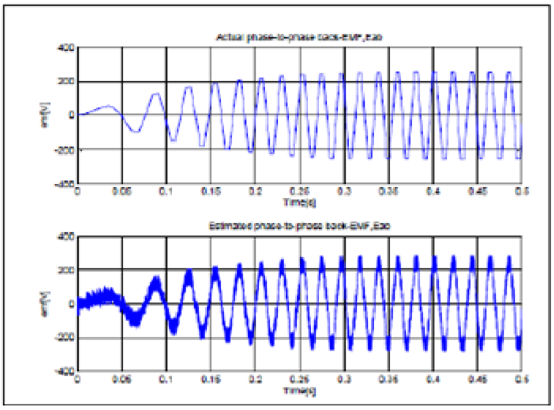

Fig. 6: Actual and estimated Back EMF

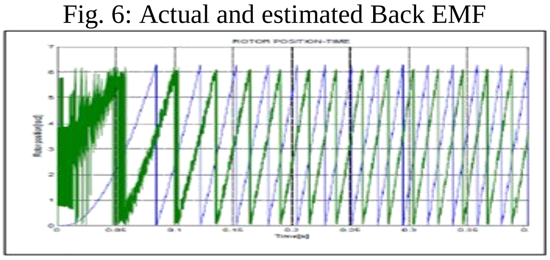

Fig. 7: Actual and Estimated rotor position

From the analysis of these results, it is shown that the estimated outputs are accurate. However there is a problem of chattering effect in the estimated waveforms. By neglecting that effect of chattering, sliding mode observer is a very good sensorless method for the estimation of phase-to-phase back-EMFs, rotor position and angular velocity.

IV. P,PI,PID CONTROL

The position control of electrical motor is most important due to various nonlinear effects like load and disturbances that affect the motor to deviate from its normal operation. The position control of a motor is to be widely implemented in machine automation [1].

A. Proportional Controller:

In this control method, the control system acts in a way that the control effort is proportional to the error. The control effort is proportional to the error in a proportional control system, and that's what makes it a proportional control system [1]. In a proportional controller, steady state error tends to depend inversely upon the proportional gain, so if the gain is made larger the error goes down.

B. PI Control

The combination of proportional and integral terms is important to increase the speed of response and also to eliminate the steady state error.

$$u(t) = K_p e(t) + k_i \int e(t)dt \qquad (21)$$

C. PID Controller:

The PID controller has proportional, integral as well as derivative so these control actions [1].The additive combination of proportional action, integral action and derivative action is called as PID action. It is defined by the differential equation

M=(κχ/Τι)∫εδτ+κχε+κδ[δ/δτ]ε+M (22)

Where Ti = Integral time, Td = Derivative time,
M = manipulated variable,
Kc = proportional sensitivity,
M = constant, e = error.

Astrom and Hagglund described an automatic tuning, called auto tuning method, an alternative to Zeigler-Nichols continuous cycling method. This method has the following features: The auto tuner uses a relay with dead-zone to generate the process oscillation. The period Tu is found simply by measuring the period of the process oscillation. The continuous cycling method has some of the disadvantages as the trial and error method. However, the continuous cycling method is less time-consuming than the trial and error method because it requires only one trial and error each.

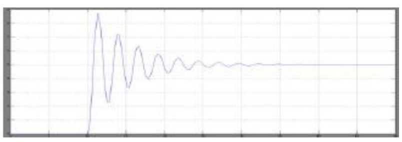

Fig.11(a): Response of dc motor with P-Controller

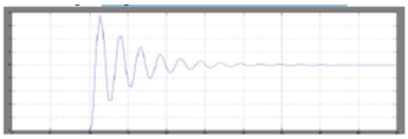

Fig.11(b): Response of DC motor with PI-Controller

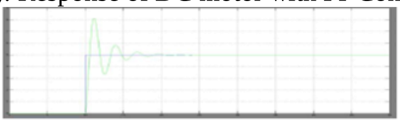

Fig.11(c): Response of a DC motor with PID Controller

V. CCSVM BASED CONTROL

A novel Current Controlled Space Vector Pulse Width Modulation (CCSVPWM) technique for Brushless Direct Current (BLDC) motor drives, with a view to reduce torque ripple is proposed. This control method improves the system performance with low torque ripple thus making it suitable for immense applications employing electromechanical actuators. BLDC motor connected to a voltage source inverter. since the motor is considered as a balanced load with an unconnected neutral 4]. For this three phase power inverter, there are eight possible switching states. Six of them lead to non-zero phase voltages and the two interchangeable states lead to zero phase voltages. When mapped in a 2D-frame fixed to the stator using Concordia transformation, the six non-zero phase voltages form the vertices of a hexagon.

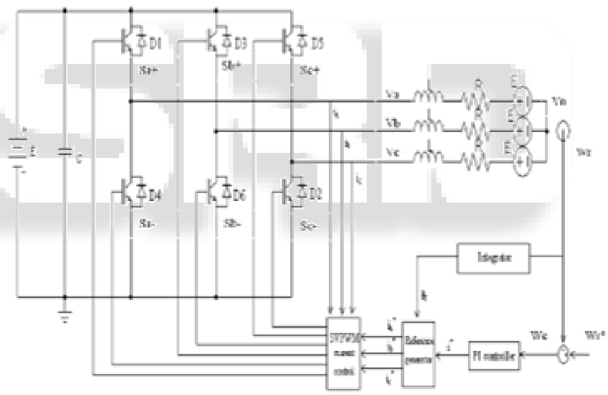

Fig.12: SVPWM FOR BLDC MOTOR

A. Current Controlled Algorithms

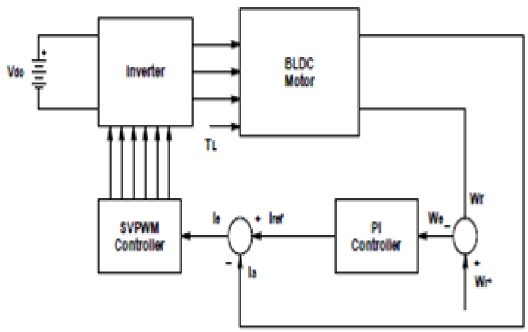

Fig.13: block diagram of SVPWM current control algorithm

The reference currents (Iref) are generated by using PI controller, speed feedback (wr) and reference speed (wr*).The actual values of the three stator currents are measured, compared with the reference currents and the errors (ie) computed. These error currents are compared with a triangular wave and the corresponding gate signals are obtained [4].The simulated results of phase current (Iabc), back emf (Eabc), speed (N) and torque (T) waveforms for the conventional method are shown in Figure 7. The motor is allowed to run at 1500 rpm and the trapezoidal back emf waveform has a maximum value of 64V, while the quasi-rectangular phase current is with a maximum value of 4.8 A. The load torque vacillates between 2.08 Nm to 3.78 Nm, resulting in a torque ripple of 29.01%. The THD of the phase current is 24.33 %.

B. Bipolar PWM Method

The shaft torque (from 2.5 Nm to 3.5 Nm) and ripple (33.67%). The THD of the phase current is also reduced to 16.67 %

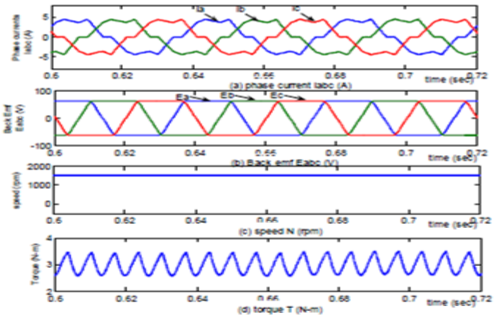

Fig.14 Current, back emf, speed and torque waveforms with Bipolar PWM method

C. CCSVPWM Technique

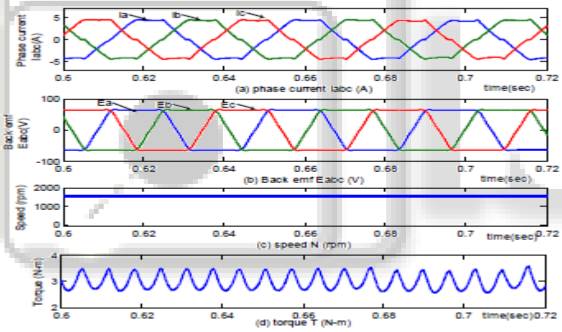

Fig.15 Current, back emf, speed and torque waveforms with CCSVPWM

The shaft torque varies from 2.64 Nm to 3.45 Nm while the torque ripple is 13.3% and the phase current THD is 9.84 %

Method	Shaft torque(Nm)	Torque ripple(%)	THD of phase current(%)
Conventional	2.08-3.78	29.01	24.33
Unipolar PWM	2.2-3.6	24.13	24.19
Bipolar PWM	2.5-3.5	16.67	13.24
VIVM	2.5-3.4	15.25	21.68
CCSVPWM	2.64-3.45	13.30	9.84

Table I

The above table shows the effectiveness of CCSVPWM technique.

VI. FUZZY LOGIC PI CONTROLLER

The controller uses three fuzzy logic controllers and three PI controllers. The fuzzy logic control is learned continuously and gradually becomes the main effective control. BLDC motor has trapezoidal back EMF and quasi-rectangular current waveform. Fuzzy logic can be considered as a mathematical theory combining multi-valued logic, probability theory, and artificial intelligence to simulate the human approach in the solution of various problems by using an approximate reasoning to relate different data sets and to make decisions. It has been reported that fuzzy controllers are more robust to plant parameter changes than classical PI or controllers and have better noise rejection capabilities [3]. The flux distribution in BLDC motor is trapezoidal and therefore the d-q rotor reference frames model is not applicable.

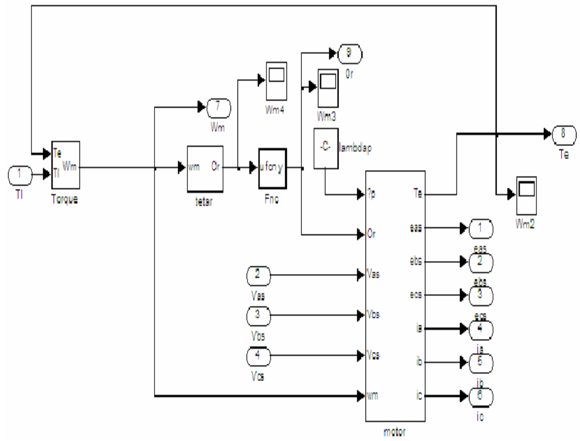

Fig.16 Fuzzy Logic PI controller fed BLDC Drive

A. Controllers

Speed controller

The speed of the motor is taken and compared with the reference speed using summer. The resulting error is estimated as, $w_e=w_r-w_r{*}$ The resulting error is given to the PI controller. The transfer function of the PI controller has the following. $G_s(s)=k_p(1+1/T_is)$ where $T_i=k_p/k_i$ known as the integral time constants. are the proportional and integral gains, respectively.

Current controller

The output of the speed controller is reference torque and the reference current is derived from the torque. The 3-phase reference currents can be obtained.

B. Fuzzy Logic PI Controller For BLDC Motor

In the past decade, fuzzy logic techniques have gained much interest in the application of control system [3]. They have a real time basis as a human type operator, which makes decision on its own basis. We present the controller which includes three dual inputs but single rule for the fuzzy logic and three PI controllers in different sampling time, as shown below.

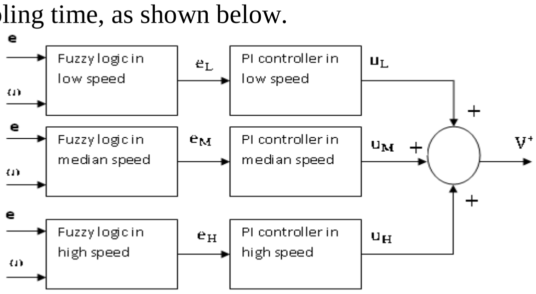

Fig. 17: Fuzzy logic PI controller.

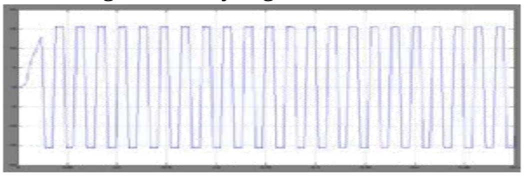

Fig. 18(a): Back EMF with variable Load

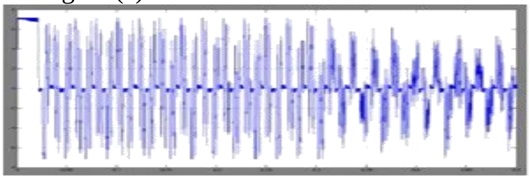

Fig. 18(b): Stator current with variable Load

In the past decade, fuzzy logic techniques have gained much interest in the application of control system. They have a real time basis as a human type operator, which makes decision on its own basis.

VII. CONCLUSION

It was proved that Sensor less DTC control of BLDC Drive for sinusoidal ac motors where both torque and flux are controlled, simultaneously. This method provides fast torque response compared to vector control. Results of Sliding mode observer technique shows that The performance of SMO with saturation functions for the electromagnetic torque estimation, rotor speed and position estimation and estimation of back-EMFs are verified under DTC scheme. It was revealed that P, PI and PID controller used in these BLDC motor. The position control of electrical motor is most important due to various nonlinear effects like load and disturbances that affect the motor to deviate from its normal operation. The position control of a motor is to be widely implemented in machine automation.

In the view of Current Controlled Space Vector Pulse Width Modulation makes the drive move towards reduction in harmonic. It is suitable for a BLDC motor drive are evaluated with relevant waveforms and their effectiveness in torque ripple reduction has been highlighted. The CCSVPWM method, which is found to be more efficient in reducing the torque ripples, will serve to enhance the usage of BLDC motor drives in electromechanical actuators. Fuzzy Logic implementation brought the BLDC motor drive to achieve different load torque. As the load torque varies the speed of the BLDC motor remains constant. Hence it can be concluded that depending on the requirement availability of resources decides the method to be implemented for control of BLDC drive.

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