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Reduction of Losses and Comparision of Sensor and Sensor less Control of Four-Switch Inverter Fed Permanent Magnet Brushless DC Motor for Low Cost Commercial Applications

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ABSTRACT
The main purpose of this paper is to develop low costfour-switch brushless dc (BLDC) motor drives for practical industrial applications. Permanent Magnet Brushless DC (PMBLDC)machines are more popular due to its simple structure and low cost. Improvements in permanent magnetic materials and power electronic devices have resulted in reliable, cost effective PMBLDC drives, for many applications. PMBL motors find applications in diverse fields such as domestic appliances and automobiles due to its low cost and performance. Modelling, simulation and experimentation of drives with new converter configuration and control schemes are essential for making this drive competitive. In this paper, a comparative study between sensor and sensor less control of four-switch Inverter fed PMBLDC is discussed and Simulation model using transfer function of BLDC motor is presented.
Keywords - PMBLDC Motor, Simulation models, sensor less, Fuzzy logic controller.

I. INTRODUCTION

Because of the distinct advantages of high efficiency, high power density and minimal maintenance, the Permanent Magnet (PM) Brushless DC machine is becoming increasingly attractive for industrial and electric vehicle (EV) applications. A brushless DC motor (BLDC) is a synchronous electric motor which is powered by direct current electricity (DC) and has an electronically controlled commutation system; instead of a mechanical commutation system with brushes. It has all the good advantage of DC drives and eliminating the drawbacks using electronic commutation. So in this motor current and torque, voltage and rpm are related linearly. Normally from the Hall Effect sensor, the signal for commutation is generated. But using these sensors the size of the BLDC motor will become larger and when space will be a main constraint, BLDC motor fails to meet the same. BLDC Motors are extensively used in domestic and automobile industries. The market is too competitive so cost reduction and higher performance will be the prime importance. Cost reduction in BLDC motor drives can be achieved by two methods one topological approach and second control approach. In the topological approach, the number of switches, sensors and associated circuitry used to compose the power converter is minimized. Normally for the BLDC Motor drive six switches inverter topology is used. By reducing the no of switches the cost reduction can be achieved. Moreover switching and conduction losses can be reduced. So here Four Switch VSI (FSVSI) topology is attempted. By using the Sensor less control the cost of the For extensive system testing and evaluation program, detailed computer modelling and simulation is being developed. Modelling of the PMBLDC machine and the controller are essential for evaluating their performance. Each of the simulators allows setting of the input parameters of the drive as well as the setup of certain load torque and speed profiles in order to evaluate the drives. In this paper the modelling of BLDCM is explained with transfer function model. The simulation of sensor and sensor less control of drive is done in Matlab/Simulink. Control with sensor, the controller is used Fuzzy logic Controller and in sensor less control the method is used terminal voltage sensing.

II. TRANSFER FUNCTION MODEL

The dynamics of the machine are described by a set of differential equations [1]. The electrical and mechanical equations can be obtained from the equivalent circuit shown in Figure 1.
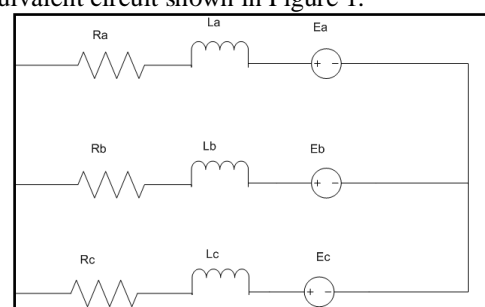

Figure 1. Equivalent circuit of BLDCM

To attain the electrical equations for a BLDC machine, basic circuit analysis was used to find the per-phase voltage as shown below. The equation is only shown for phase-A to neutral since the equations for phase B and C only differ in the subscript notation.

$$V_{an} = i_a(t)R_a + L_a \frac{di_a}{dt} + e_a(t) \qquad (1)$$

From the equivalent circuit Figure 1., the circuit equation of the motor in phase variable form are given in equation (1) where Van the applied phase voltages, ea is the induced back emf, ia is the phase currents. La, is the self inductances of the phases and Ra is the resistance of each phase. The mechanical equation that relates the machine's angular velocity to the developed electromagnetic torque, load torque, and motor parameters is given in equation (2),

$$T_{em} = B\omega(t) + J\frac{d\omega(t)}{dt} + T_L \qquad (2)$$

where Tem(t) is developed electro-magnetic torque, TL is load torque, B is viscous friction constant, J is rotor moment of inertia, _ is the angular speed of the motor. But we know that Electromagnetic torque and back emf are given by equations (3) and (4),

$$T_{em} = K_t i_a(t) \qquad (3)$$
$$e_a(t) = K_e \omega(t) \qquad (4)$$

where K_t is torque constant and K_e motor constant.

Taking Laplace transformation of the respective quationsand rearranging the terms equations (5) and (6) are obtained.

$$i_a(s) = \frac{V_{an}(s) - K_e\omega(s)}{R_a + sL_a} \qquad (5)$$

$$\omega(s) = \frac{T_{em}(s) - T_L}{B + sJ} \qquad (6)$$

From the above equations it is possible to draw the model of the BLDC motor as shown in Figure 2. From the Figure 2transfer function of the system is presented in equation (7).

$$\frac{\omega(s)}{V(s)} = \frac{\frac{k_t}{JL_a}}{s^2 + s\frac{iR_a + BL_a}{JL_a} + \frac{BR_a + k_t k_e}{JL_a}} \qquad (7)$$
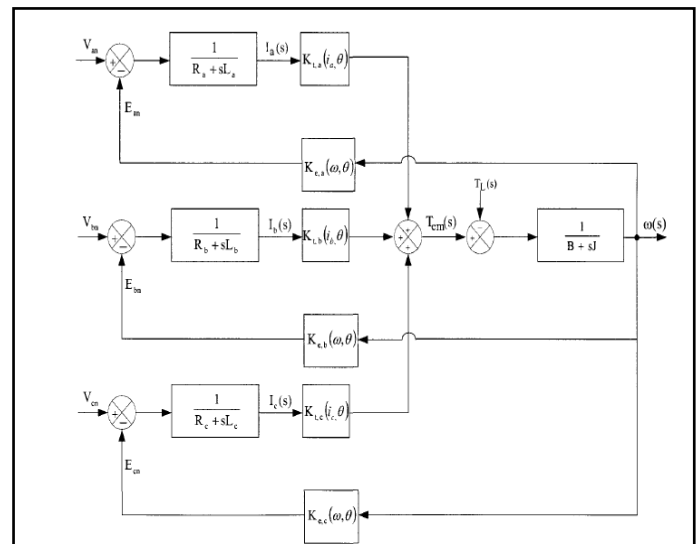

Figure 2. Transfer function model of PMBLDC

III.   FOUR SWITCH CONVERTER TOPOLOGY

The cost reduction of controllers for PMBLM drives can be considered with the topologies with more than one switch per phase, but less than conventional two switches per phase .But according to the working of BLDCM, at a time only two phases are conducing and the third phase is inactive [2-5].A BLDC motor needs quasi-square current waveforms, which are synchronized with the back-EMF to generate constant output torque and have 120 degree conduction and 60 degree non-conducting regions. However, in the four-switch converter, the generation of 120 degree conducting current profiles is inherently difficult Though cost saving is achieved, it introduces distortions in the uncontrolled phase. This problem is solved by using hysteresis current control. In this method pwm pulses produced by the switching ON and OFF the switch when the phase current crosses the Hysteresis Band. The simulation model is as shown in Figure 3 and output waveform is shown in the Figure 4.
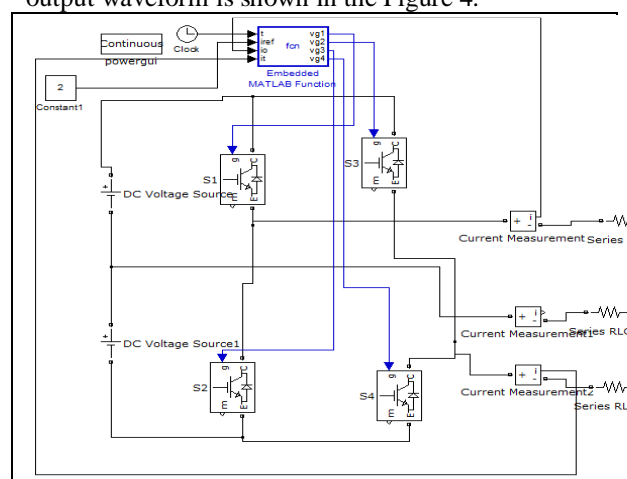

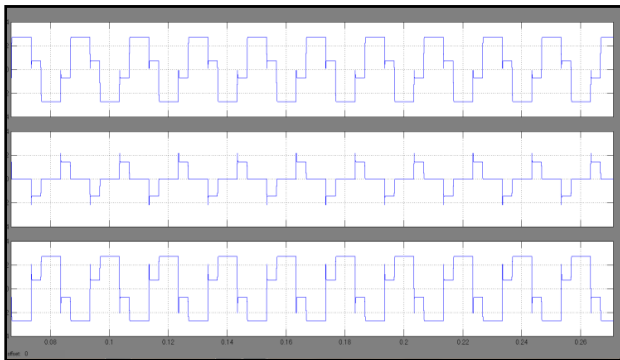Figure 3 Four Switch converter using Direct Control method

Figure 4 Phase current waveform of Four switch converter

IV. SENSOR LESS CONTROL

A low cost BLDC motor drive with reduced parts that is by reducing the number of switches from six to four is to be developed. The implementation of a low cost, reduced parts BLDC motor is desired with high system reliability. Most of the sensors less methods for a six-switch inverter BLDC motor drive are not directly applicable to the four-switch inverter [6-10]. The main reason is that in the four-switch topology, some methods detect less than six points, and other commutation instants must be interpolated via software. This paper presents a novel sensor less method for four-switch BLDC motor drive based on zero crossing points of stator line voltages.
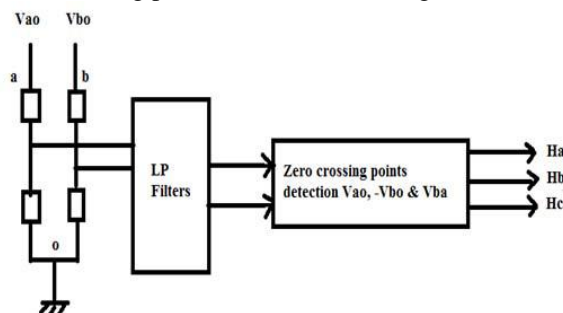

Figure 5 Position Sensing Using Line Voltages

In four switch converter topology the third phase is connected in between midpoint of two capacitors. Assume that point to be 'O' and is connected to the ground. With point O as reference, the three line voltage waveforms, Vao ,Vbo and -Vbo . Therefore, by detecting the zero crossing points of three line voltages, six commutation points are obtained. From this commutation points the virtual hall effect signals are produced. Three line voltages are derived from terminal voltages Vao and Vbo. They have higher magnitude compared to back EMF voltages that is $\sqrt{3}$ times phase voltages plus drop voltage on the stator impedance.
written as equation (8) to (10).

From figure 5 the terminal voltage equation can be written as equation (8) to (10).

$$V_{ao} = R_a I_a + L_a \frac{di_a}{dt} + e_{an} + V_{no} \qquad (8)$$

$$V_{bo} = R_b I_b + L_b \frac{di_b}{dt} + e_{bn} + V_{no} \qquad (9)$$

$$0 = R_c I_c + L_c \frac{di_c}{dt} + e_{cn} + V_{no} \qquad (10)$$

Because the drive employs the Direct Current Control (DPC) method, in order to make the current as quasi square waveform in accordance with the trapezoidal back emf, motor adopts 120 degree conducting mode and only two phases are energized at one time. So, the current in the two phases has the same amplitude and opposite direction, while in the third phase, the current is zero. The phasor representation of Four switching topology is shown in Figure 6.
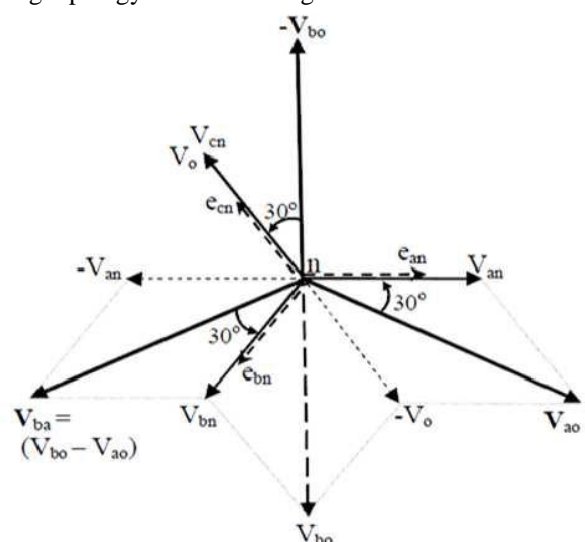

Figure 6 Line to line voltage representation

A complete simulation of the system is done in Simulink of the MATLAB environment. The system consists of a BLDC motor with the dc link voltage and inverter. The performance of the machine is studied in open loop. A constant speed operation of the drive is simulated in closed loop. Control is achieved via terminal voltage sensing. The three voltage functions are used to get the commutation points. A voltage divider circuit is used first, followed by low pass filter (second order Butterworth) and then a zero crossing detection circuit to get the virtual hall signals. A d- q model of the BLDC motor done is considered in a rotor reference frame and an analytical simulation using a m-file is carried out to study the torque-speed characteristics of the motor under steady state. The simulation diagram is shown in Figure 7 and results are given in Figure 8
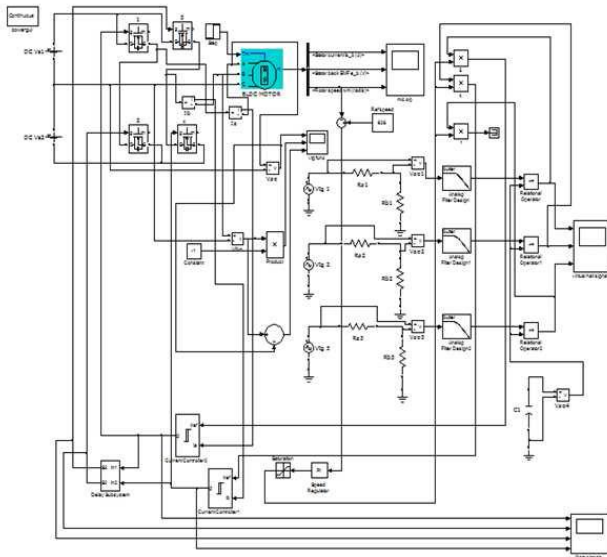
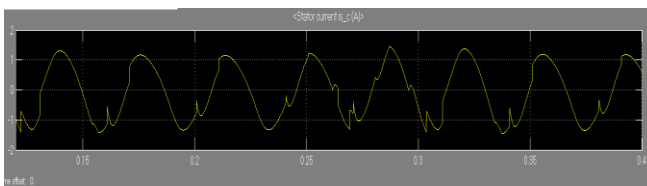Figure 7 Simulink diagram for sensor less control

Figure 8 Stator current for Phase C

In analytical simulation method the torque speed characteristics using M-file.The steady-state torque is given by equation 11.

$$T_{em} = \frac{3}{2}\frac{P}{2}[\lambda_m i_{qs}^r + (L_d - L_q)i_{qs}^r i_{qs}^r] \qquad (11)$$

For steady-state operation, Φ_v is constant and represents the angular displacement between the peak value of the fundamental component of Vas and the q-axis fixed in the rotor. The values of V_{qs}^r and V_{ds}^r ds are determined by the firing of the driving inverter. But for most applications, the
common operating mode is used where the conditions are $\Phi_v = 0$, whereupon $V_{qs}^r = \sqrt{2}V_S$ and $V_{ds}^r = 0$. Also assuming $L_d = L_q$, the expression for torque is given in the equation (12).

$$T_{em} = \frac{3}{2}\frac{P}{2}\left[\left\{\frac{r_s\lambda_m^r}{r_s^2 + \omega_r^2 L_S^2}\right\}V_{qs}^r - \omega_r\lambda_m^r\right] \qquad (12)$$

The graph is not entirely linear but approximately linear only in the region where $T_e \geq 0$ and $\omega_r \geq 0$. It is not linear for the entire speed range. The simulation result analytical simulation is shown in the Figure 9.
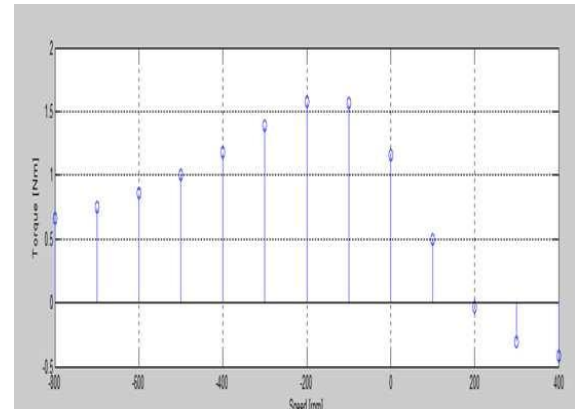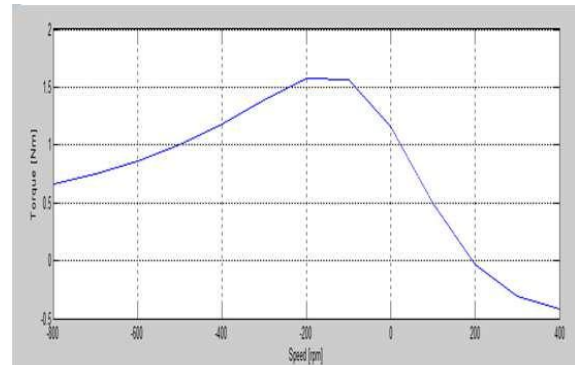

Figure 9 Torque Speed characteristics obtained by Analytical method

V.   FUZZY LOGIC CONTROLLER

Fuzzy logic controller is used for simulation of BLDC Motor with sensor. Three hall effect sensors are connected the other end of the motor and they are separated by 120 degree mechanically. A Fuzzy Logic Controller (FLC)[11-12] uses fuzzy logic as a design methodology, which can be utilized for developing linear and non-linear systems for embedded control. FLC techniques need less development time, have better performance and are good replacements for conventional control techniques, which require highly complicated mathematical models. A fuzzy logic controller does not require an exact mathematical model. It however requires knowledge-based set of heuristic rules. These rules are impressive and are expressed in terms of linguistic variables. The steps involved in the design of fuzzy controller are fuzzification, rule definition and defuzzification. For the fuzzy controller necessary data required for the simulation is given in Table 1. The two inputs given are error and change in error. The output is the reference current for the Hysteresis controller. All three membership functions are Triangular. The input and output membership functions are shown in Figures 10 to 12. The fuzzification rule is entered using the rule editor of the fuzzy toolbox as shown in Figure 13. The simulation diagram is shown in Figure 14. The overall simulation diagram with controller, four-

switch inverter and BLDC motor model is shown in Figure 15.

TABLE 1: PARAMETERS FOR THE SIMULATION OF FUZZY CONTROLLER

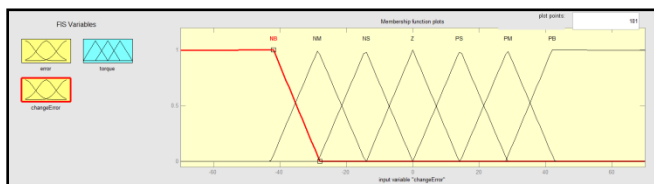| Name	'FuzzyBldc.fis'
Type	'mamdani'
and method	'min'
or method	'max'
defuzzMethod	'centriod'
impMethod	'min'
aggMethod	'max'
input	[1x2 struct]
outpule	[1x1 struct]
rule	[1x49 struct]
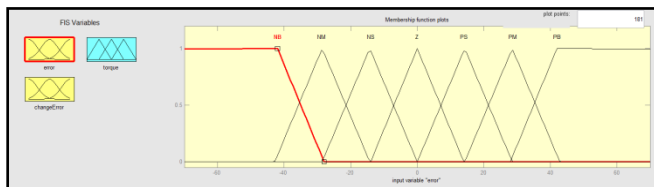
Fig10: Membership Function of Error

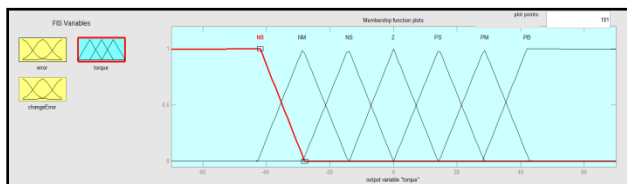Figure 11 Membership Function of Change Error

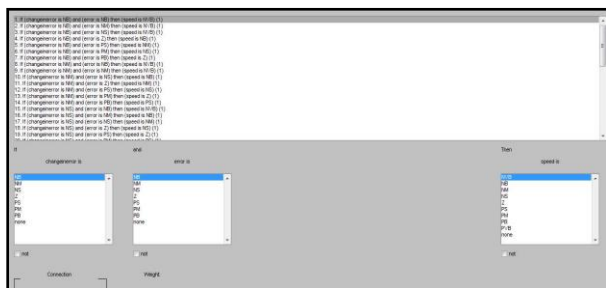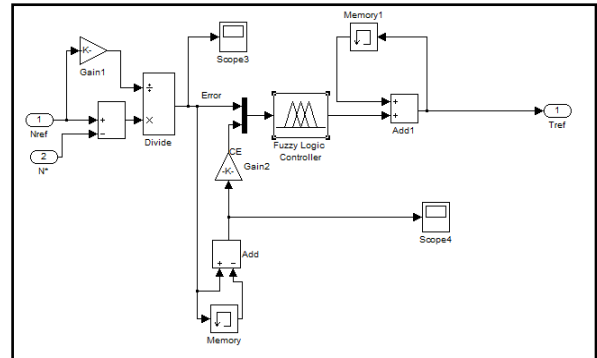Figure 12 Membership Function of Reference Current

Figure 13 Rule Editor

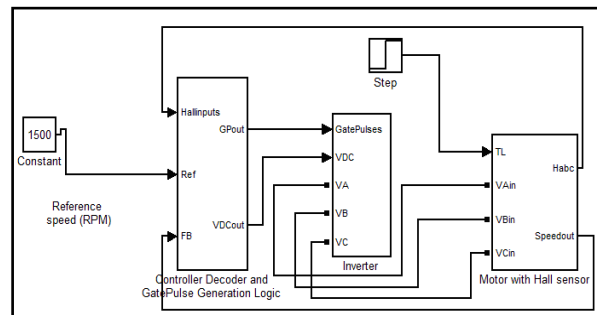Figure 14 Fuzzy controller with hysteresis controller

Figure 15 Controller, four-switch inverter and Motor model

The measured motor speed from the BLDC drive is compared with the reference speed producing the error which is given to the controller in the model. By decoding output of the hall sensor signals, gate pulses for the three phase inverter are generated. The current output from the fuzzy output is fed to hysteresis controller(current limit control) [13] is used for making the phase currents smoother. Simulation duration is given as 0.6 sec and solver is fixed step,ode4 (Runge-gutta). The simulations are performed for fuzzy controller and the results are given in fig11-17.
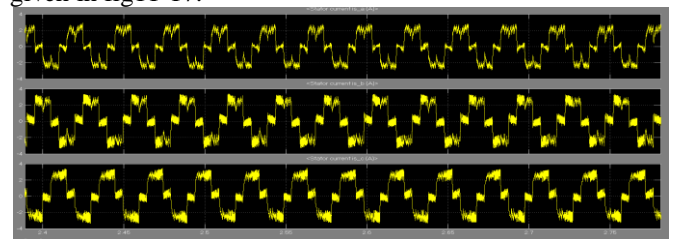

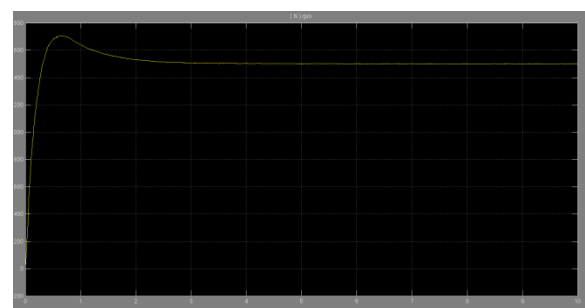Figure 16 Phase Current Using Fuzzy controller

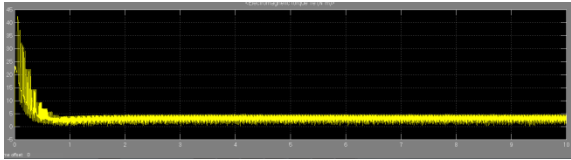Figure 17 Speed profile of the drive for Fuzzy controller

Figure 18 Torque profile of the drive for Fuzzy controller

VI.   CONCLUSION

In this paper, the transfer function model is explained. The simulation is performed in MATLAB /SIMLINK motor model fed by four-switch inverter with hysteresis current control first with sensor less and then Fuzzy controller with the hall effect sensors. The current waveforms are rectangular without any distortion due to the hysteresis control. From the phase voltages the virtual Hall Effect signals are produced and thus applicable in four switch inverter topology. The sensorless method via terminal voltage sensing will overcome the disadvantages of back emf method. But the sensorless control method is not suitable for higher speed changes. The fuzzy controller i.e sensor control responds faster and smoother to reference speed changes. But if low cost is the primary concern and motor speed is not an issue, then sensorless control will be the better choice. The hardware implementation is simplified with the use of DSP processor with built-in features and easy C programming interface of Code Composer studio. The hysteresis current control is yet to be implemented in hardware.

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