Modeling and Speed Control of a Brushless DC Motor Using Fuzzy-PI Controller

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Abstract— **Permanent magnet brushless DC motors (PMBLDC) have started finding a wide applications in industries because of their high power density and simplicity of control. The BLDC motor consists of a permanent-magnet rotor, and the stator windings are wound in a such a way that the back electromotive force (EMF) is trapezoidal in nature and hence requires rectangular-shaped phase currents for Stator to provide a constant torque. The trapezoidal back EMF shows that the mutual inductance between the stator and rotor is non-sinusoidal. Therefore, there are no particular advantage in transforming the machine equations into the well-known d-q equations, which is generally done in the case of electrical machines with sinusoidal back EMF's like PMSM. this paper also presents a Hybrid Fuzzy Proportional Integral controller for the speed control of Brushless DC (BLDC) motor. A fuzzy controller provides better speed response for start-up while PI controller has good compliance over variation of load torque but has slow settling response. Hybrid controller has an benefit of integrating the superiority of these two controllers for better control performances. In this paper, the conventional PI controller is integrated with Fuzzy Logic controller to make hybrid control system with merits of both. The comparative study between PI, Fuzzy, and Fuzzy-PI controller is also shown in the paper. The various dynamic characteristics of BLDC Motor are analyzed for variation in load torque conditions through simulations.**

Index Terms- Trapezoidal back EMF, torque pulsations, sinusoidal back EMF.

I. Introduction

The dc servo is facing a serious competition from AC servos for the applications from fractional to a range of 30 HP, the available ac servos include the induction, permanent-magnet synchronous (PMSM), and brushless dc motors (BLDCM) [l]. The BLDCM has a trapezoidal back EMF, and rectangular stator currents are needed to produce a constant electric torque while the PMSM has Sinusoidal Back EMF. The hysteresis or pulse width-modulated (PWM) current controllers are used to maintain the actual currents flowing into the motor as close as possible to the rectangular reference values.

Although some steady-state analysis has been done**,** the modelling, detailed simulation, and experimental verification of this servo drive has not been considered in the literature. Hence the purpose of this paper is to fill this gap. It is shown that, because of the trapezoidal back EMF and the consequent non-sinusoidal variation of the motor inductances with rotor angle, a transformation of the machine equations to the well-known d, ***q*** model is not the best approach for modelling and simulation. Instead, the natural or phase variable approach provides many advantages. This paper also presents a Hybrid Fuzzy Proportional Integral controller for the speed control of Brushless DC (BLDC) motor. BLDC motors have many merits over DC motors and induction motors. A fuzzy controller provides a better speed response for start-up while PI controller has good compliance over variation of load torque but has slow settling response. Hybrid controller has an benefit of integrating a superiorities of these two controllers for better control performances. In this paper, the conventional PI controller is integrated with Fuzzy Logic controller to make hybrid control system with advantages of both. Also it shows the comparative study between PI, FLC, and hybrid Fuzzy-PI controller for the same. The dynamic behavior of BLDC Motor is also analyzed for varied load torque conditions through various simulations in MATLAB SIMULINK environment.

II. MODELLING OF BLDC.

Even though this approach has been already proposed, the back EMF is not represented as a Fourier series as is done in [10].Here we have used piecewise linear curves to generate the back EMF according to the position of the rotor. Gibbs phenomenon that occurs due to the truncation of the higher order harmonics necessary when using the Fourier series approach can be avoided using this technique. Using this model of the Brushless DC Motor , a detailed simulation and analysis of a BLDCM speed servo drive is given. The simulation includes the state variable model of the motor and speed controller and a real-time model of the inverter switches. Although the switches are assumed to be ideal devices, the software developed is flexible enough to incorporate their turn-on and turn-off times. Every instance of opening or closing of a power switch is simulated to determine the current oscillations and consequent torque pulsations. How the hysteresis window size effects the motor torque pulsations is investigated, and the effects of hysteresis and PWM current controllers on the drive system performance are also examined.. The mathematical model of the BLDCM is developed.

The BLDCM has permanent magnets on the rotor side and three stator windings . As both the retaining sleeves and rotor magnets have high resistivity, the rotor-induced currents can be neglected & damper windings are not modelled. Hence the circuit equations of three windings in phase variables are shown below.

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + d/dt \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

where it is assumed that for all the windings the stator resistances are equal. The back EMF's e_a, e_b, and e_c have a trapezoidal shape as shown in Fig 2. Let L_{aa}, L_{bb} and L_{cc} be the self inductances and L_{ab}, L_{bc} and L_{ca} be the mutual inductances for phase a,b and c respectively. Assuming further that there is no change in the reluctance angle of the rotor.

Now due to symmetry of motor

$L_{aa}=L_{bb}=L_{cc}=L$ and $L_{ab} = L_{bc} = L_{ca} = M$ (2)

Hence

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + d/dt \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (3)$$

$i_a + i_b + i_c = 0$

therefore we get

$Mi_a = - (Mi_b + Mi_c)$ (4)

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + d/dt \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

$T_e * \omega_m = (e_a i_a + e_b i_b + e_c i_c)$

$T_e = (e_a i_a + e_b i_b + e_c i_c) / \omega_m$ (5)

$d/dt(\omega_m) + B\omega_m = Te + Tl$

Therefore the equation for motion is

$d/dt(\omega_m) = Te + Tl - B\omega_m$ (6)

The currents i_a, i_b, and i_c, needed to produce a steady torque without torque pulsations**.** A transformation can be with AC motors that have sinusoidal back EMF, from the phase variables to *d, q* coordinates whether it is in the standstill, rotating or synchronously rotating reference frames. Inductances that vary sinusoidally in ***a, b,* c** frame will become constants in the ***d,*** *q* reference frame. As the back EMF is non-sinusoidal in the BLDCM this means that the mutual inductance between the stator and rotor is also non-sinusoidal, hence transformation to a *d, q* reference frame cannot be easily accomplished. A chance of finding a Fourier series of the back EMF, in that case the back EMF in the *d, q* reference frame will also consist of many terms. This is considered too to be difficult, hence ***a, b,* c** phase variable model already developed shall be used without any further transformations in it.

III HYBRID FUZZY-PI CONTROLLER

The purpose of the hybrid control scheme is based on compensation for overshoots and undershoots in the transient response and minimizing the steady state error. A PI controller when used in combination with FLC such that near steady state operation, PI controller takes over the control eliminating the disadvantage of the FLC. Similarly when away from the operating point FLC dominates and eliminates the occurrence of overshoots and undershoots in drive response. The superiority of both fuzzy and PI controller are integrated together by using a switch as shown in Fig.5.

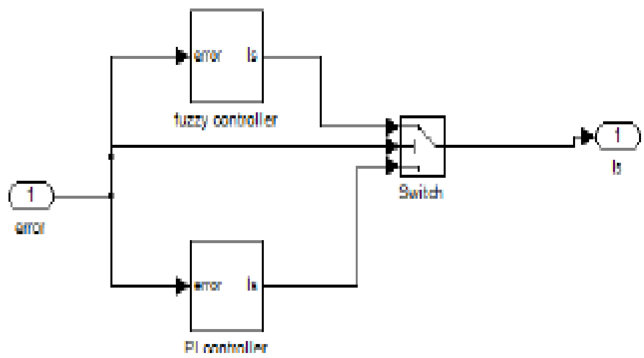

Fig.1 Hybrid Fuzzy-PI controller.[2]

The position of the switch is controlled by the timing of the simulation and the error in the speed such that when the error is high the switch goes into fuzzy mode and when it is low the switch goes in PI mode the condition for switching is

Switch Positioning:

When e > E and t < T switch goes into Fuzzy Mode

When e < E and t > T switch goes into PI Mode.

To prove the control strategies used a simulation is being done in Matlab/Simulink on a Brushless DC motor using the parameters mentioned the following table.

TABLE 1
THE PARAMETERS OF THE MOTOR

Sr No	Motor Parameters	Value
1	Stator Phase Resistance (Ohms)	2.8750
2	Stator Phase Inductance(H)	8.5e-3
3	Torque Constant(N.m / A_peak)	1.4
4	Back EMF flat area (degrees)	120
5	Inertia (kg.m^2)	0.8e-3
6	viscous damping (N.m.s)	1e-3
7	pole pairs	4
8	Power (W)	120
9	Number of Phases	3
10	Supply Voltage (V)	12 V

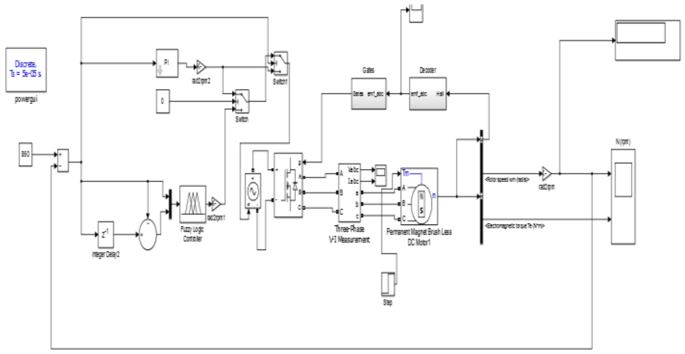

Fig.2.Simulink model of speed control of BLDC motor using Fuzzy-PI

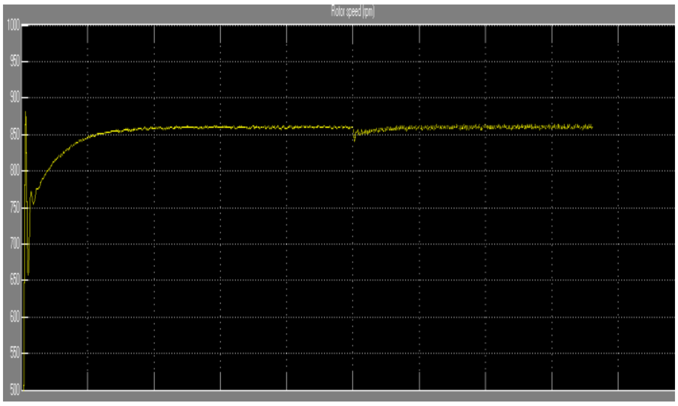

Fig .3 Rotor speed in running condition at 0.5 with sudden loading at 0.5

FLC has two inputs namely- Error (E) and change in Error (CE) .The output of this controller is voltage (V).Input and Output variables are have five membership functions each. Triangular shape for the membership function has been chosen because of its simplicity. Thus, 25 rules have been constructed to perform the desired task. 'Mamdani' type of Fuzzy is incorporated. 'MOM' (Middle of Maximum) method of Defuzification has been used because of its faster response.Fig.7 below shows Fuzzy membership functions for inputs (E,CE) and output (V) for the fuzzy controller

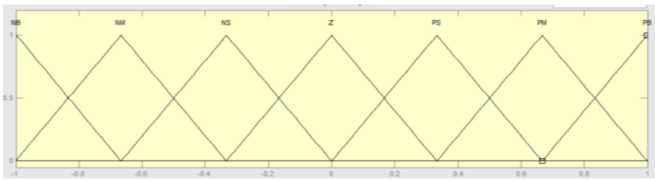

Fig 4 Plot for Membership function, error

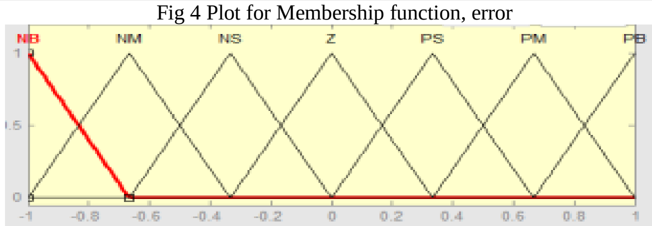

Fig.5 Plots of Membership functions changes in error.

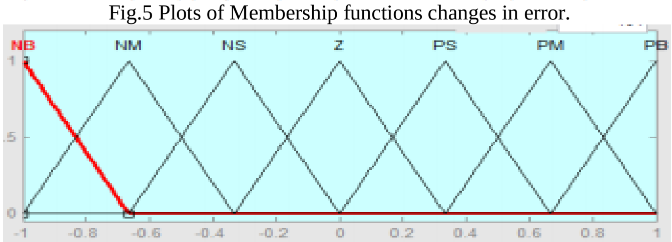

Fig.6. Output (V) membership functions of Fuzzy Logic Controller.

Fig.7 shows a comparison of the output speed responses of the three controllers with a reference of 860rpm. A sudden load of 0.2N-m was introduced to the system at time t=l sec. PI controller has initial peak overshoots and undershoots whereas FLC settles down without any peak shoot. When a sudden load was applied, PI settles down at the reference speed following a dip of 1-2 rpm whereas FLC settles faster but with a large speed error.

In case of Hybrid Fuzzy-PI, the response initially follows the path of FLC and when Load torque was varied, it followed the path of PI controller. Hybrid Fuzzy-PI consist of a 'switch subsystem' which works such that when speed error is large and clock time is less than a threshold value, control will be switched to Fuzzy and vice-.Four major characteristics compared/discussed here are:-

a) Peak Overshoot/Undershoot: how much the peak level is higher/lower than the steady state, as compared against the steady state.

b) *Settling Time*: the time taken by the system to converge to its steady state. It is expressed in seconds.

c) *Controller Score*: It is calculated by multiplying Maximum overshoot with settling time. It should be least.

d) *Steady-state Error*: the difference between the steady state output and the desired output. Here it is expressed in rpm

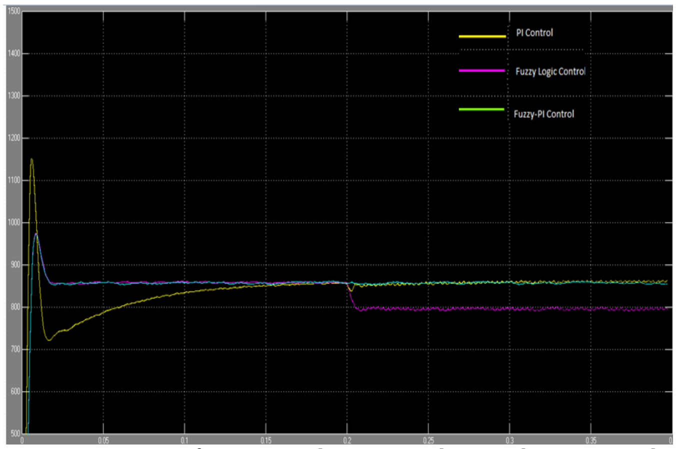

Fig 7 Comparison of PI, Fuzzy and Fuzzy-PI under normal operating mode and when suddenly loaded ref speed is 860 rpm.

Table 3
Comparison of PI Fuzzy and Fuzzy-PI controllers for No load and Sudden load conditions.

At No-Load			
Controller	**PI**	**Fuzzy**	**Fuzzy-PI**
Peak Overshoot (%)	32.55	11.62	11.62
Peak Undershoot (%)	15.11	0	0
Settling time (sec)	0.2	0.025	0.025
Controller Score (%* sec)	6.51	0.2905	0.2905
Steady state error (rpm)	2	1	1
At Sudden Load application			
Controller	**PI**	**Fuzzy**	**Fuzzy-PI**
Peak Overshoot (%)	0.116	0	0
Peak Undershoot (%)	2.325	8.31	0.34
Settling time (sec)	0.01	0.05	0.001
Controller Score (% * sec)	0.116	0	0
Steady state error (rpm)	2	70	0-1

It can be clearly seen that PI controller has high Peak Overshoot/ Undershoot, at both no load and with load torque conditions. Also settling time is comparatively higher for PI controller. Fuzzy controller gives a smooth response, without any peak overshoots and has a faster response than PI controller. But FLC settles with large speed error upon load variation. Hybrid Fuzzy-PI controller shows a comparatively better response for all the three factors considered i.e. percentage overshoots, settling time, steady state error at both no load and with load torque considered.

VI. CONCLUSION

The modelling procedure presented in this paper helps in simulation of BLDC motors. The performance evaluation results shows that, such a modelling is useful in studying the drive system before taking up the dedicated controller design. Three controllers have been discussed namely- PI, Fuzzy and Fuzzy-PI. Also, a comparative study of these controllers have been done which shows that the performance of the fuzzy logic controller is during under transient conditions, whereas that of the proportional plus integral controller is superior near the steady state condition. The combined benefits of these two controllers can be obtained with hybrid PI-fuzzy speed controller. Mathematical modelling of the BLDC motor is studied and on this basis, the modeling & simulation of the proposed control system is made. The behavior of the system using PI controller, fuzzy controller and hybrid PI- fuzzy controller are compared. It is shown through simulation that the performance of the Hybrid PI- Fuzzy controller is better than using PI controller and fuzzy controller alone for the speed control of BLDC motor.

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