A Novel Fuzzy Logic Based Sensor less Speed Control of Position Sensorless BLDC Servo Drive

R.Manikandan, K.R.Priyadharsini, R.Arulmozhiyal

Abstract*: *The development of advanced motor drive has been increases rapidly, because of their higher performance and reliability. The Sensorless control of permanent magnet brushless DC motor is presented in this paper. The fuzzy PI controller is developed for controlling the speed of the PMBLDC motor drive. Here the Sensorless control is obtained based on indirect back EMF detection which was justified by the observation that the position sensing is obtained indirectly from zero crossings of terminal voltages. Closed loop speed control is made with estimated speed from the stator voltage, so the drive proposed without any shaft mounted devices like position sensor and speed sensors. The performances of the proposed fuzzy logic controller based PMBLDC motor drive were investigated and the results are compared with conventional PI controller. Also the sensorless result scheme is compared with sensor control. In this Sensorless technique the cost of mechanical components such as sensors and cables are eliminated. The simulated results of conventional and fuzzy controller is compared and results illustrates that the FLC gives better dynamic performance also it is more robust for industrial speed control drive applications.

Index Terms*: *Brushless DC motor, fuzzy logic controller, PI controller, MATLAB, Sensor and Sensorless control, Zero cross detection.

I. INTRODUCTION

In recent years BLDC motors are used in high performance drive system because of its advantages. The brushless DC motor has trapezoidal electromotive force (EMF) and quasi rectangular current waveforms. These motors are widely used in industrial applications, robot manipulators and home appliances where speed and position control of motor are required. To sense the rotor position it requires the position sensor such as resolver or encoder or hall sensors. Brushless DC Motors are driven by DC voltage but current commutation is controlled by solid state switches. The commutation instants are determined by the rotor position. The zero crossing of back EMF can be detected to determine the commutation sequence without hall sensors. These methods are based on, using back EMF of the motor detection of the conducting state of freewheeling diode in the unexcited phase, back EMF integration method detection of stator third harmonic voltage components[1]. Back EMF estimation methods typically rely on the zero crossing detection of the EMF waveform. The back EMF estimation is done by sensing the terminal voltages with respect to a virtual neutral point. Detecting the free-wheeling diode conduction in the open phase gives the zero-crossing point of the back EMF waveform. This approach of rotor-position sensing is work in lower speed. The main drawback of this scheme is the requirement of six additional power supplies for the comparator circuits to detect current flowing through the free-wheeling diode [2]. An extended Kalman filter estimator for a brushless dc motor has been developed by Bozotertic and Martin jadric for speed and rotor position estimation but in this method uncertainty in modeling and measurements [3]. Integrating the back EMF waveform of the unexcited phase is another method to extract the position information. This type of approach is less sensitive to switching noise but low speed operation is poor [4]-[6].

This paper presents the indirect back EMF detection which is directly obtained from sensing the terminal voltages by properly choosing the pulse width modulation. This method does not involve any integration since the line voltages are used the requirement of neutral potential has been eliminated [7]-[8]. It also eliminates the common mode noise. The approaches to zero crossing detection were used to start reliably the BLDC motor drive in Sensorless operation.

The Sensorless control based drive by conventional and fuzzy PI controller is presented in this paper. The conventional speed control methods have the following difficulties, it depends on the accuracy of the mathematical model of the system and the expected performance is not met due to the load disturbances [9]-[10]. The fuzzy controller gives the better dynamic performance as well as error reduction. The fuzzy logic technique is used to control the speed of BLDC motor under variable as well as fixed conditions. Recently this technique has been applied to fast response linear servo drive giving superior results [11]-[14].

This paper is organized as follows. The first section gives the introduction about the paper. The second section of the paper is about the proposed Sensorless control of BLDC drive. Design of speed controller with conventional and fuzzy technique is discussed in the third section. The fourth section deals with the simulation work carried through MATLAB environment. The fifth section is about the results and discussions. The final section presents the conclusion and future work of the paper.

II. SENSORLESS SCHEME FOR BLDC MOTOR DRIVE

Manufacturing cost of a BLDC motor drive can be reduced more by elimination of position sensors and speed sensors. Sensorless control is the only choice for some applications where hall sensors cannot function reliably because of harsh environments. Consider a BLDC motor having three stator phase windings connected in star Fig.1. The BLDC motor is driven by a three-phase inverter in which the devices are triggered with respect to the rotor position.

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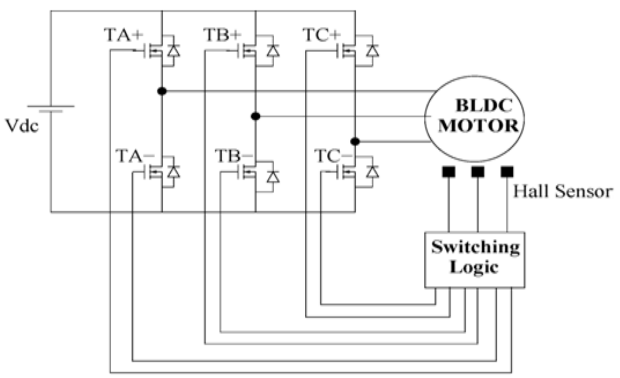

Fig.1. Overview of BLDC motor drive

The phase A terminal voltage with respect to the star point of the stator V_{an} is given in as

$$V_{an} = R_a i_a + L_a \frac{di_a}{dt} + e_{an} \quad (1)$$

Where, R_a is the stator resistance of the 'A' phase, L_a the phase inductance, e_{an} the back-EMF and I_a the phase current. Similar equations can be written for the other two phases.

$$V_{bn} = R_b i_b + L_b \frac{di_b}{dt} + e_{bn} \quad (2)$$

$$V_{cn} = R_c i_c + L_c \frac{di_c}{dt} + e_{cn} \quad (3)$$

The line voltage V_{ab} may be determined as,

$$V_{ab} = V_{an} - V_{bn} \quad (4)$$

It is evident from that Fig.2, during this interval (shaded portion) the back EMF transits from one polarity to another crossing zero. Therefore, the operation enables detection of the zero crossing of the phase B EMF. Similarly, the difference of line voltage enables the detection of zero crossing of phase C back EMF when phase B and C back EMFs are equal and opposite. Therefore, the zero-crossing instants of the back EMF waveforms may be estimated indirectly from measurements of only the three terminal voltages of the motor.

These line voltages can, however, be estimated without the need for star point by taking the difference of terminal voltages measured with respect to the negative dc bus. The method is thus quite general and is not dependent on the ideal nature of the back EMF waveform. The proposed Sensorless method uses this approach to estimate the zero-crossing instants of the back EMF from the terminal voltages of the motor from which the correct commutation instants are estimated. The corresponding commutation table is shown in table 1.

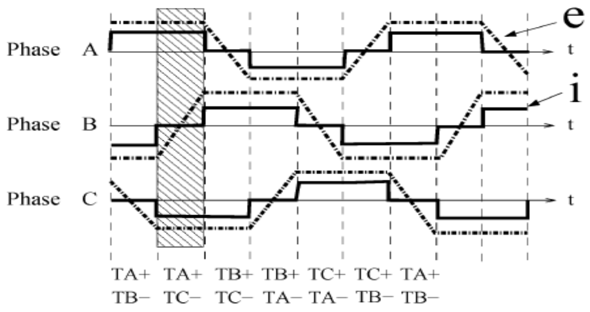

Fig.2. Phase currents and back EMF waveforms of BLDC Motor.

TABLE I – COMMUTATION TABLE

Rotor position	A	B	C	T_A+	T_A-	T_B+	T_B-	T_C +	T_C -
0°-60°	+1	-1	0	1	0	0	1	0	0
60°-120°	+1	0	-1	1	0	0	0	0	1
120°-180°	0	+1	-1	0	0	1	0	0	1
180°-240°	-1	+1	0	0	1	1	0	0	0
240°-300°	-1	0	+1	0	1	0	0	1	0
300°-360°	0	-1	+1	0	0	0	1	1	0

The approach to zero crossing detection was used to reliably start the BLDC machine in sensorless operation. With the zero crossing instant of the back-EMF known, thirty degree electrical delay is obtained. The ideal trapezoidal back-EMF slope lasts for 60 degrees when EMF changes from positive to negative flat portion or vice versa. It is equally divided into30 electrical degrees on either side from the zero crossing instant of the back-EMF.

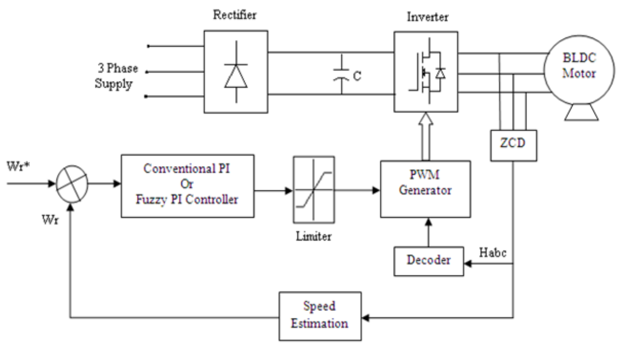

Fig.3. Block diagram of Sensorless BLDC control drive

Block diagram for Sensorless scheme of proposed brushless DC motor is show in Fig.3. In the block diagram PMBLDC motor speed is sensed without any shaft mounted devices so it is Sensorless control. With the zero crossing point of the terminal voltages, hall position and speed can be obtained. The estimated speed is compared with set speed and error speed is given into controller unit. The fuzzy PI controller and/or conventional PI controller gives the response. The output of the controller response is given to the limiter. Then it is fed to PWM generator. It generates the corresponding pulse which is given as input for inverter. The output of the inverter is fed to 3phase PMBLDC motor to control the speed.

III.DESIGN OF SPEED CONTROLLER

A. Conventional speed controller

The conventional PI controller block model is given in Fig 4.

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It is one of the most common approaches for speed control in industrial electrical drives.

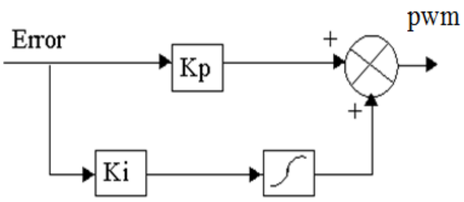

Fig.4. Conventional PI controller

In general, because of its simplicity, and the clear relationship existing between its parameters and the system response specifications a very common method to determine the Kp and Ki constants of the PI controller is the method of Ziegler-Nichols. After applying unit step input closed loop response should be observed. It should be in the shape of S like curve and it should settle at steady state. From the response, the value of *L* and *T* are obtained by drawing tangent at inflection point of *S* like curve as shown in the Fig 5. From the controller parameter the value of proportional gain and integral gain are calculated. Based on the rules Ziegler-Nichols, the values of K_p and K_i are found out as 0.5 and 0.05 respectively.

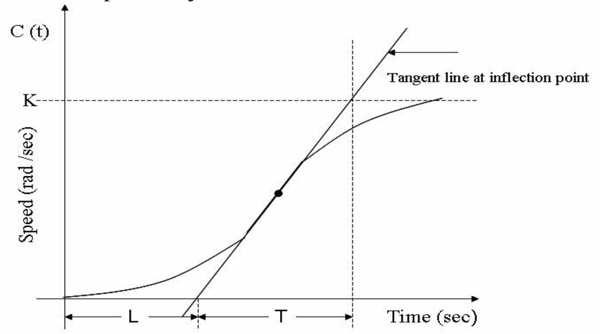

Fig.5. Ziegler-Nichols method output response

The main drawback in this controller it depends on the accuracy of the mathematical model of the system and also the expected performance is not met due to the load disturbance. To overcome this drawback we go to fuzzy controller at proposed technique. A fuzzy control algorithm for a process control system embeds the intuition and experience of an operator, designer and researcher. The control does not need an accurate mathematical model of a plant, and therefore it suits well to a process, where the model is unknown or ill defined.

B. Fuzzy PI controller

To determine a fuzzy rule from each input-output data pair, the first step is to find the degree of each data value in every membership region of its corresponding fuzzy domain. The variable is then assigned to the region with the maximum degree, when each new rule is generated from the input-output data pairs, a rule degree or truth is assigned to that rule, where this rule degree is defined as the degree of confidence that the rule does in fact correlate to the function relating voltage and current to angle. Every training data set produces a corresponding fuzzy rule that is stored in fuzzy rule base. A fuzzy rule base or knowledge is in the form of two dimensional tables, which can be looked up by the fuzzy reasoning mechanism. Fig.6 shows the block diagram of fuzzy PI controller. The speed error is calculated with comparison between reference speed and actual speed. Speed error and changing speed error are fuzzy controller inputs.

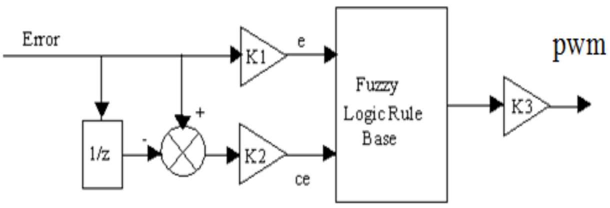

Fig.6. Fuzzy PI controller

The Input variables are normalized with a range of membership functions specified and the normalization factors are named as K1, K2 and de-normalized by using K3. These normalized factors play a vital role for the FLC. The factors K1and K2 are chosen to normalize the speed error 'e' and the change of speed error 'ce'. The fuzzy logic controller initially converts the crisp error and change in error variables into fuzzy variables and then are mapped into linguistic labels. Membership functions of input 'e', 'ce' and output 'pwm' are shown in Fig.7 which consists of two inputs and one output. The triangular membership functions are used for all the fuzzy set of the input and output vectors. Fig.7 is similar to the output response of all functions such as 'e', 'ce' and 'pwm'.

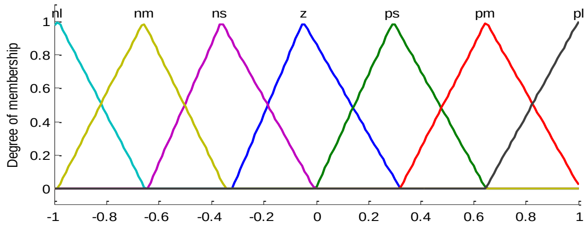

Fig.7. Membership Functions for 'e', 'ce' and 'pwm'

There are seven MFs for the input e, ce, and output u as pwm. All the MFs are symmetrical for positive and negative values of the variables. The linguistic labels are divided into seven groups. They are nl - negative large, nm - negative medium, ns - negative small, z- zero, ps-positive small, pm - positive medium, pl - positive large.

The surface view of the fuzzy PI controller is shown in Fig.8, where as the x-axis is error 'e' and y-axis change is error 'ce' and z-axis is output 'u' as command PWM.

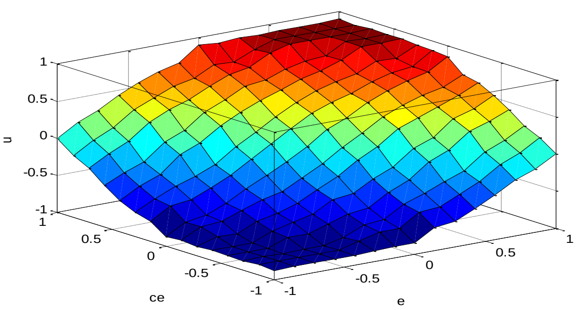

Fig.8. Surface View of fuzzy controller

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TABLE II - FUZZY RULE-BASED MATRIX

ce \ e (u)	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

The fuzzy-rule-based matrix used for the proposed BLDC servo motor specific FLC algorithm is shown in table II. The top row and left column of the matrix indicate the fuzzy set of the variables ‘e’ and ‘ce’ respectively, and the MFs of the output variable ‘pwm’ are shown in the body of the matrix. There are 7*7=49 possible rules in the matrix. Mamdani type inference is used for inference engine.

IV. SIMULATION OF BLDC SENSORLESS SCHEME

Simulink model for the sensorless control of BLDC motor drive is depicted in Fig 9. The closed loop controller for a three phase BLDC motor is modeled using MATLAB/SIMULINK environment. The permanent magnet synchronous motor with trapezoidal back EMF is modeled as a brushless DC motor.

Fig.10. which provides the subsystem block for the conventional as well as fuzzy PI. The fuzzy logic controller initially converts the crisp error and change in error variables into fuzzy variables. Fuzzy system shows that there are two input ‘e’, ‘ce’ and only one output ‘pwm’.The triangular membership functions are used to generate the control signals in this proposed technique. The virtual hall sensor subsystem in the main model provides position information and estimated speed of BLDC motor. Decoder used to run the motor in self controlled mode and the PWM generator is used to vary the speed.

Table III provides the Entire Machine Parameter Values for simulation Work which is fully done through using friendly environment as MATLAB/SIMULINK Software.

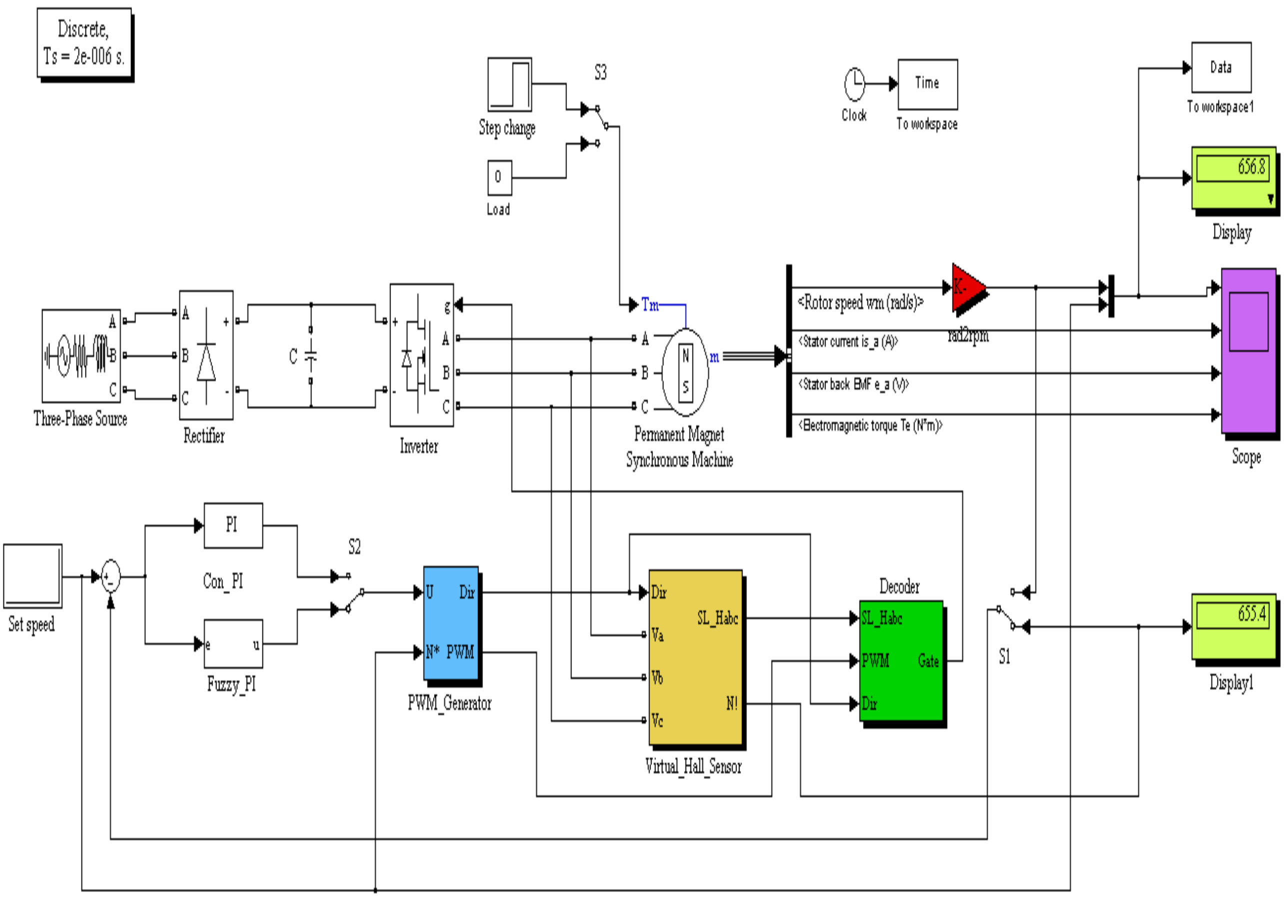

Fig.9. Simulink Model of Sensorless BLDC Motor drive

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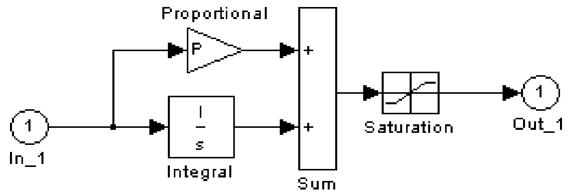
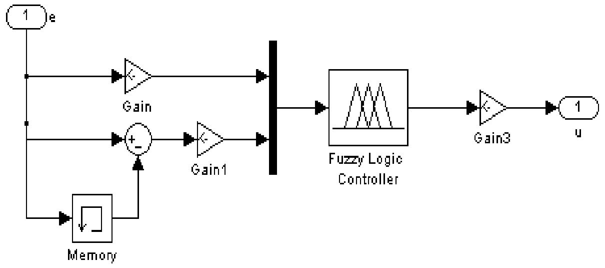


a. Conventional PI controller



b. Fuzzy PI controller
Fig.10. Speed controller subsystem

TABLE III – MACHINE PARAMETERS

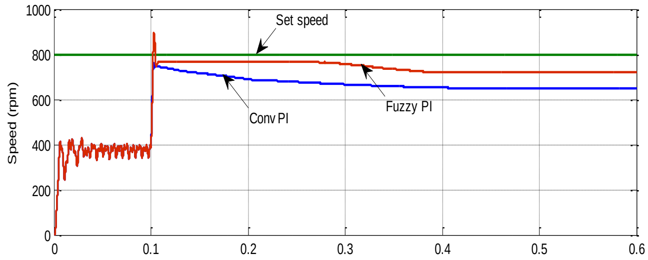
Parameters	Symbols	Values	Units
Pole pairs	P	4	-
Speed	ω	4000	rpm
Stator Resistance	Rs	2.875	Ω
Stator Inductance	Ls	8.5	mH
Voltage	v	310	V
Friction	F	1e-3	Nms
Inertia	J	0.3e-3	$Kg.m^2$
Back EMF (Trapezoidal)	E	120	Degree

V. RESULTS AND DISCUSSION

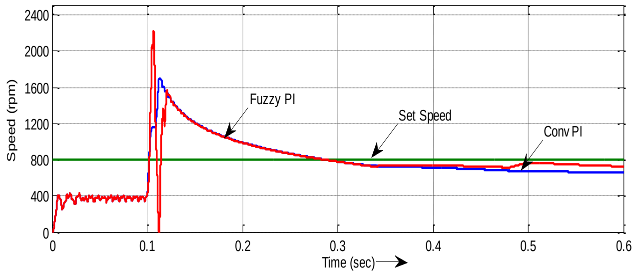
Several tests were performed to evaluate the performance of the proposed FLC based Sensorless control of Permanent Magnet BLDC motor drive system which is simulated in MATLAB/SIMULINK environment. To evaluate the performance of the system, series of measurements have been accomplished. The results can be divided into three groups the first one is normal response, second is the step change speed, constant speed at load disturbance (load impact) and finally current, torque, back EMF for different conditions.. Here the result shows that the motor will run at open loop condition up to 0.1sec.

After 0.1 sec there is a sufficient back EMF will generate, so the drive will shift to sensorless closed loop mode. In sensor control speed only determined through sensor control but the position of the system is in sensorless manner. So in sensorless technique also drive will be run in open loop manner up to 0.1 sec. Finally sensorless mode results are compared with sensor control operation for both conventional and fuzzy PI based controllers.

Fig.11 gives an idea about the speed curve of motor at no load condition for 800 rpm in both conventional PI and fuzzy PI controller response under sensor (a) as well as sensorless control in (b). From the first figure, it is understood that the conventional PI response settles the actual speed at 0.45 sec, but in case of fuzzy PI at 0.35 sec and the steady state error of conventional PI is 18% but in fuzzy PI only 3% is presented in sensor mode of control.

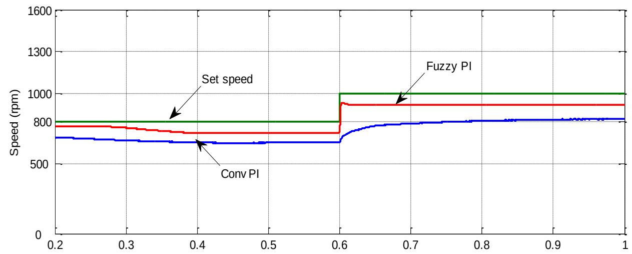


a. Sensor based control

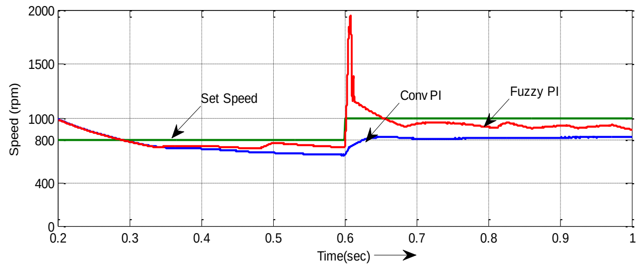


b.Sensorless based control
Fig.11. Starting response at 800rpm

Similarly second plot represents the speed curve of motor at no load condition for 800 rpm in both conventional PI and fuzzy PI controller response for sensorless operation. From the figure, it is understood that the conventional PI response settles the actual speed at 0.4 sec, but in case of fuzzy PI at 0.32 sec and the steady state error of conventional PI is 15% but in fuzzy PI only 5% is presented.



a. Sensor based control



b. Sensorless based control
Fig.12. Speed step up response at 800rpm to 1000rpm

Fig.12 Exhibits the 800 rpm to 1000 rpm speed step up response for no load condition. From the result of first plot, set speed changes at 0.6 Sec for step up.

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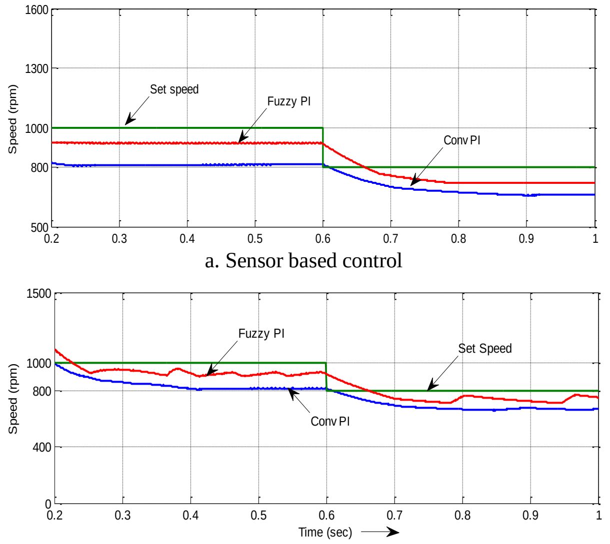
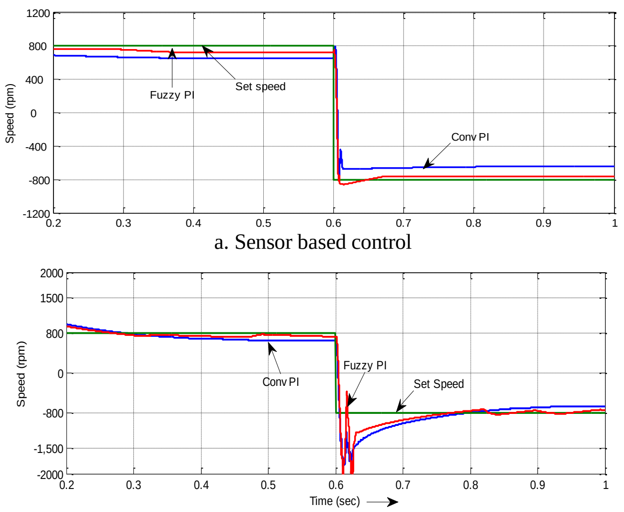
It is observes that the conventional PI settles at the time of 0.1 sec for step up response. But in case of fuzzy PI settles at the time of 0.02 sec for step up response. From the result of second one sensorless speed control action takes place. Here the set speed changes at 0.6 Sec for step up. It is observes that the conventional PI settles at the time of 0.1 sec for step up response. For fuzzy PI settling time is at the period of 0.08 sec for step up response.



b. Sensorless based control

Fig.13. Speed step down response at 1000rpm to 800rpm

Fig.13 put on view about the 1000 rpm to 800 rpm speed step down response for no load condition. From the result of first plot, set speed changes at 0.6 Sec for step down. It is observes that the conventional PI settles at the time of 0.25 sec. But in case of fuzzy PI settles at the time of 0.2 sec in sensor based control mode. From the result of second figure sensorless speed control action takes place. Here the set speed changes at 0.6 Sec for step down. It is observes that the conventional PI settles at the time of 0.15 sec. For fuzzy PI settling time is at the period of 0.1 sec.



b. Sensorless based control

Fig.14. Speed Reversal response at 800rpm to-800rpm

The speed reversal performance of motor at no load condition for sensor control with the speed of 800 rpm to -800rpm in both conventional PI and fuzzy PI controller as obtained which is presented in Fig14.a. From the figure, it shows that the conventional PI response settles the actual speed at 0.06 sec, but in case of fuzzy PI at 0.05 sec and the steady state error of conventional PI is 18% but in fuzzy PI only 3% is presented.

The speed reversal performance of motor at no load condition for 800 rpm to -800rpm in both conventional PI and fuzzy PI controller for sensorless action as obtained which is shown in Fig.14.b. From the figure, it shows that the conventional PI response settles the actual speed at 0.23 sec, but in case of fuzzy PI at 0.15 sec and the steady state error of conventional PI is 12% but in fuzzy PI only 3% is presented.

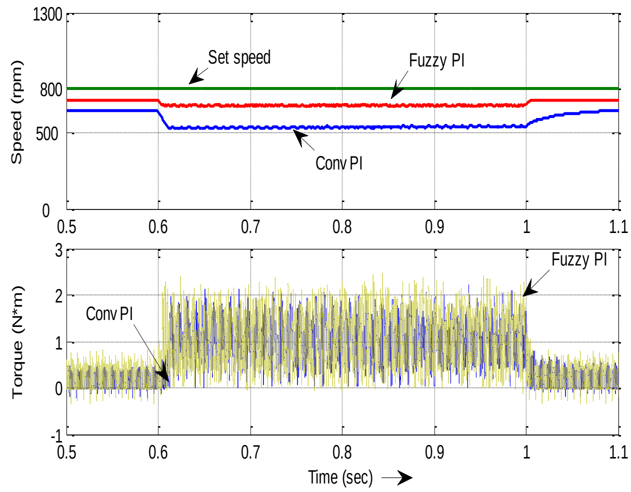


Fig.15. Load Impact at 800rpm for sensor speed control

The drive response with sudden change of load at 800 rpm is shown in Fig.15 for sensor speed control operation. From the above figure, at t= 0.6 sec, the load is changed to 1n/m and it's keep until 1sec.Also the corresponding torque has been obtained.

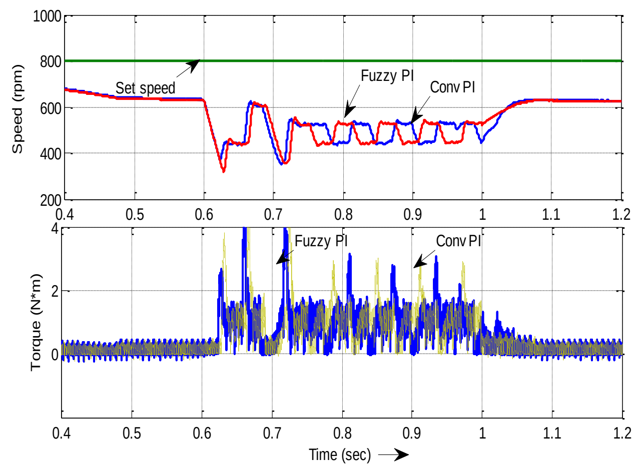


Fig.16. Load Impact at 800rpm for sensorless speed control

Correspondingly, the drive response with sudden change of load at 800 rpm for sensorless speed control operation is shown in Fig.16. From the above figure, the load is changed to 1n/m at t= 0.6 sec, and it's keep until 1sec. Also the corresponding torque has been obtained.

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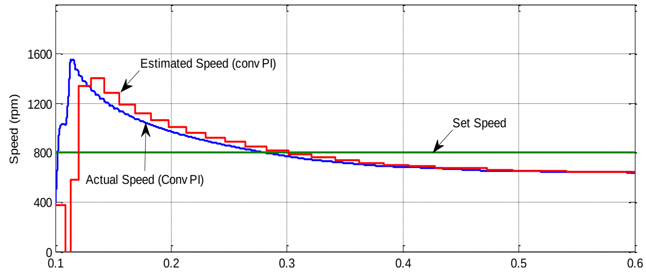
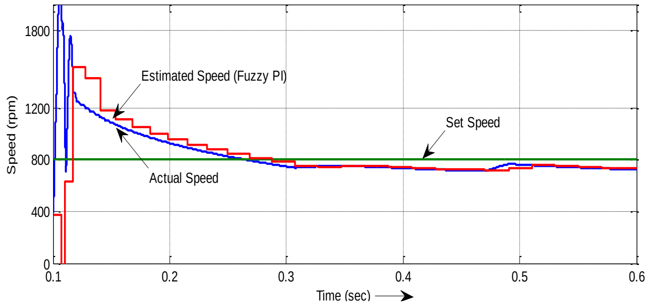
During the load impact condition the torque gets increased and speed of the motor initially gets reduced and it will maintain constant speed after a few seconds.



a. Conventional PI control



b. Fuzzy PI control

Fig.17. Estimated speed and actual speed at 800rpm

The result shown in Fig.17 is the estimated and actual speed at 800 rpm under the condition of no-load for conventional and fuzzy PI controller. Here both estimated and actual speed gets settled to nearest values. The response is smooth and no oscillation in the case of present fuzzy PI control scheme.

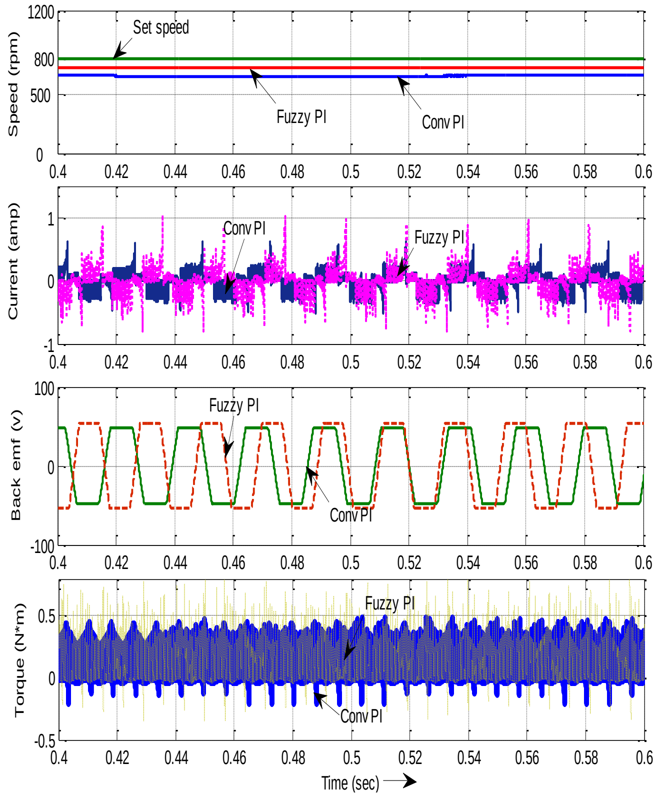


Fig.18. Currrent, Back EMF,torque output at 800rpm for sensor speed control

Current, back emf and torque has been obtained for sensor as well as sensorless operation at the speed of 800 rpm as shown in Fig.18 and Fig.19 respectively. The above response of current, back EMF and torque is compared with both fuzzy and conventional PI controller.

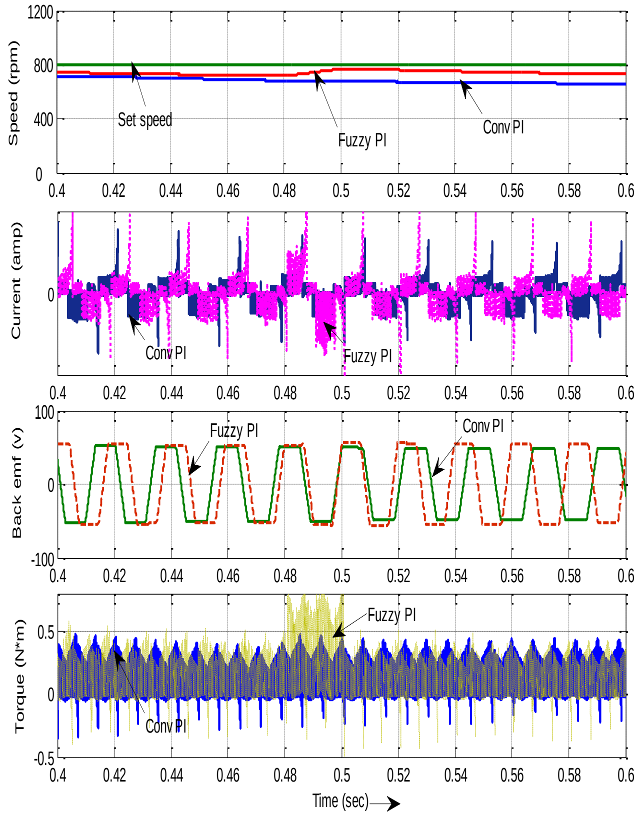


Fig.19. Currrent, Back EMF,torque output at 800rpm for sensorless speed control

TABLE IV

COMPARITIVE TABLE FOR SENSOR BASED SPEED CONTROL

Controllers		Conventional PI			Fuzzy PI		
Parameters / Speed/load		% of Mp	Ts (sec)	% of error	% of Mp	Ts (sec)	% of error
Constant speed with no load (800 rpm)		-	0.35	18	10	0.25	3
Speed change with no load	(800-1000) rpm	-	0.1	17	-	0.02	6
	(1000-800) rpm	-	0.25	15	3	0.2	5
Speed reversal with no load (800rpm to -800rpm)		-	0.06	18	2.5	0.05	3
Load change	800rpm (0-1 n/m)	-	0.03	15	-	0.01	8

Table IV and Table V shows the simulation result comparison with both controllers at various speed and load condition for sensor and sensorless control schemes.

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In sensorless control scheme the overshoot is little high when compared to sensor control action.

TABLE V. COMPARITIVE TABLE FOR SENSORLESS BASED SPEED CONTROL

Controllers		Conventional PI			Fuzzy PI		
Parameters / Speed/load		% of Mp	Ts (sec)	% of error	% of Mp	Ts (sec)	% of erro r
Constant speed with no load (800 rpm)		85	0.45	15	150	0.3	5
Speed change with no load	(800-1000) rpm	87	0.1	18	90	0.08	5
	(1000-800) rpm	-	0.15	15	13	0.1	5
Speed reversal with no load (800rpm to-800rpm)		90	0.23	12	100	0.15	3
Load change	800 rpm (0-1 n/m)	-	1	20	-	0.1	15

Several results were simulated to evaluate the performance of the proposed FLC-based PMBLDC drive system in both sensor and sensorless speed control. The effectiveness of the proposed Fuzzy PI controller is investigated. . For all the cases, the percentage of steady state error and settling time is better for fuzzy PI controller when it is compared with conventional PI controller. But due to fast response overshoot is somewhat high in fuzzy PI. Finally sensorless speed control is closer to sensor control technique.

VI. CONCLUSION

Thus the sensor and sensorless speed control of permanent magnet brushless DC motor drive for both conventional and fuzzy PI controllers has been presented in this paper. It is found that the speed of BLDC motor can be controlled in both manner. Through this paper, the sensorless drive is almost closer to sensor drive as it eliminates the problem associated with sensor like cost, reliability and maintenance. By using fuzzy logic PI controller the motor which can run smoothly even with load transients. Furthermore, Sensorless control is the only choice for some applications where those sensors cannot function reliably due to harsh environmental conditions. In Fuzzy logic control it is not necessary to change the control parameters at any conditions. It does not happen in conventional PI. So the Fuzzy controller is more suitable for Sensorless control of BLDC drives in industrial applications.

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