A New Improved Algorithm For Speed Control Of Brushless DC Motor

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Abstract- In this work, a new hybrid algorithm has been developed by combining Particle Swarm Optimization (PSO) and Differential Evolution (DE) algorithms to obtain efficient speed control of Brushless Direct Current (BLDC) motor under various conditions. The results obtained are compared with those obtained using Fuzzy Logic Controller, Fuzzy Proportional Integral (PI) Controller and Particle Swarm Optimization (PSO) based Fuzzy PI Controller which have been developed for the same application, under the same conditions. The performance of all the controllers are analyzed under the operating conditions of, varying speed no load, varying speed at constant load, varying load at constant speed and varying speed and load simultaneously. The above-mentioned four algorithms have been developed and implemented in Matlab/ Simulink environment and it has been found that the speed regulation by the proposed hybrid PSODE-Fuzzy PI controller is well above the rated values.

Keywords - Speed Control, Brushless Direct Current (BLDC) motor, Particle Swarm Optimization (PSO), Differential Evolution (DE), Fuzzy Proportional Integral (PI) Controller.

1. Introduction

In earlier days, most of industrialists preferred the squirrel cage induction motor with advanced power electronics controller. But it had some limitations due to poor power factor and less efficiency. At this situation, some manufacturers gave importance to synchronous motor to replace the squirrel cage induction motor. It too had some limitations in electromagnetic interference, noise and speed. This led to the need for an alternate solution to industrial applications. This is the origin of the development of Permanent Magnet Brushless Direct Current (PMBLDC) motor [1],[2],[3]. Due to high efficiency, reliability, low maintenance and compact size, BLDC motors became a more popular research area for researchers worldwide. PMBLDC motor has permanent magnet as a rotor. Hence, there is no excitation loss, simple construction is realized and operation is very reliable [4],[5],[6]. Based on above advantages, it can give fast dynamic response with high efficiency. Selection of permanent magnet of the rotor is of much more importance to get highest energy density and greater residual flux density.

The Neodymium-Iron-Boron (Nd-Fe-B) rare magnets are of demand than other magnets for rotor construction, since it can give high energy density for low cost than other magnets like alnico, ceramic and ferrite [7]. With help of Nd-Fe-B rare magnet, the size of rotor of BLDC motor is decreased and performance of the motor is increased. Due to simple construction and better performance, it can fit for position control applications and medium size industrial drives. The development and innovation of power electronics devices and advancements in geometrics bring the BLDC motor in industrial, commercial and domestic applications. The advanced power electronics based PMBLDC generator play an important role in aero planes and on board ships [8],[9]. Usually BLDC motors are powered by voltage source inverter or current source inverter [10],[11]. Firing angle of this inverter is controlled by signal from the rotor position. The position of the rotor is sensed by using hall sensors, resolvers or optical encoders. BLDC motors can be more suitable for electrical vehicles and hybrid electrical vehicles due to their advantages [12],[13]. They also facilitate pollution free transport. This served as a motivation to select the speed control of BLDC motor as part of the work done in this research. Main objective of this work is to analyze the performance of BLDC motor under the various conditions by using different types of controllers.

2. Earlier Research And Studies

Vijayarajeswaran [14] developed a sensorless control scheme suitable for the speed control of brushless DC permanent magnet motor. Speed control was achieved by detecting zero crossing instant of back EMF. The TMS320F2812 controller was found to offer an easy way of real-time implementation that does not require large computation time. The performance enhanced the input power factor and thereby minimized the system Volt Ampere Reactive (VAR) requirements, in addition to yielding a regulated speed over the entire operating range.

Sivakotiah [15] developed a fuzzy logic based soft switching resonant inverter to overcome over voltage and over current problems existing in resonant converter for speed control of brushless DC motor. Fuzzy logic based soft switching resonant pole inverter was constructed using transformer, which could generate DC link voltages during chopping which minimized the drawback of soft switching. The operation principle and control scheme of the inverter were analyzed and performance of the fuzzy controller was compared with conventional PI controller.

Reddy [16] designed a simulation model for BLDC motor drive with PID controller and Hybrid Fuzzy Logic Controller (HFLC) to obtain the speed control of BLDC motor. The performance of the controllers was evaluated for variations in the load torque and speed of BLDC motor drive. A performance comparison of two controllers was also carried out by taking various performance measures such as settling time, steady state error, peak overshoot, the integral of the absolute value of the error (IAE) and the integral of the time-weighted squared error (ITSE). The results confirmed that HFLC was found to be superior, more robust, faster and flexible and was insensitive to the parameter variations when compared with conventional PI and PID controllers.

Mosavi [17] proposed a neuro-fuzzy controller based on supervisory learning for the speed control and torque control of BLDC motor under transient and steady state operations. The designed controller was a combination of Neural Networks (NNs) and Fuzzy Logic (FL), therefore had parallel processing and learning abilities of NNs and inference capacity of FL. To improve the performance of learning algorithm and there upon increase efficiency of drive, instead of usual Error Back Propagation (EBP) learning technique, a fuzzy based supervisory learning algorithm was employed. The controller had simple structure and ease of implementation. It also had high accuracy, suitable performance, high robustness and high tracking efficiency.

Kandiban [18] implemented an adaptive fuzzy logic algorithm to control the speed of BLDC motor. Speed control was obtained by tuning the PID values using adaptive fuzzy logic algorithm. The Adaptive Fuzzy had the ability to satisfy control characteristics and it was easy for computing. The experimental results verified that the Adaptive Fuzzy PID controller had better control performance than both Fuzzy PID controller and conventional PID controller.

Vanisri and Devarajan [19] presented a sensorless control of permanent magnet brushless DC motor (PMBLDC) using fuzzy controller. It was based on "indirect position sensing" method. The position detection could be derived from the voltage and current waveforms. Such position information was derived from the line voltage difference measured at the terminals of the motor instead of back-electro motive force to eliminate the harmonics. For precise control and to get desired performance, the motor was controlled using fuzzy controller. Speed control of PMBLDC motor was achieved using virtual instrumentation. This method controlled the speed for various ranges. When compared with the conventional back EMF zero crossing sensorless control, the proposed new sensorless control methods for brushless DC technique was more robust and easier to implement.

3. Materials And Methods

A. Construction of BLDC Motor

The BLDC motor has wire wound stator poles and permanent magnet in rotor. The stator has three windings in star or delta fashion. Most of the BLDC motor construction follows the star connection. The slots of the stator have one or more coils and they are interconnected to make a winding. Even number of poles is maintained by distributing all the windings over the stator peripherals. The rotor is made of permanent magnet. The magnetic flux density of the rotor is decided by the permanent magnet materials. Number of poles in the rotor can vary from two to eight pole pairs with alternate north and south poles. Ferrite and rare earth alloy magnets are used as permanent magnet material for rotor construction. Speeds of the stator magnetic field and rotor magnetic field have the same frequency. It is similar to a synchronous motor. BLDC motor is an electronically commutated motor. The commutation of BLDC motor is done by power electronic devices. To rotate the motor, stator windings are energized in a sequence and the position of the rotor is sensed by hall effect sensor which is embedded in the stator. Usually BLDC motor has three hall sensors in stator. While the magnetic poles of rotor pass near the hall sensor, they give high or low signals and indicate which pole is passing near the sensors. The sequence of commutation is determined with help of the hall sensors.

B. Theory of operation

At any instant, one of the windings is energized by positive power, the second winding is energized by negative power and third is in non energized condition. Torque is developed on the rotor by interaction between the stator flux and permanent magnet field of the rotor. Peak torque is occurred when the angle between the stator and rotor field are at 90 degrees and fall off as the fields move together.

C. Mathematical Model of BLDC Motor

Typical mathematical model of BLDC motor is described by the following equations,

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_m - M & 0 & 0 \\ 0 & L_m - M & 0 \\ 0 & 0 & L_m - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

where R is the Resistance of each phase of the stator, Lm is the Self inductance of each phase, M is the mutual inductance between any two phases, ua, ub, uc are the phase voltages, ia, ib, and ic are phase currents, ea, eb, ec are trapezoidal back EMFs.

The electromagnetic torque can be expressed as,

$$T_e = \left(e_a i_a + e_b i_a + e_c i_c\right) / \omega_r \tag{2}$$

where ω_r is the rotor speed. The torque balance equation is expressed as,

$$T_e = T_L + \frac{2J}{P}\frac{d\omega_r}{dt} + B\omega_r \tag{3}$$

where TL is the load torque, J is moment of inertia, B is damping of friction co-efficient and P is the number of poles. The rotor position θ is a function of ω_r and expressed as,

$$\frac{d\theta}{dt} = \omega_r \tag{4}$$

Fig.1 depicts the block diagram for the speed control of the BLDC motor. Speed of the BLDC motor is calculated by the rotor position. The derivative of rotor position gives the speed of the motor. The actual speed of the BLDC motor is compared with the given reference speed of the motor. The speed error and change in speed error are given as inputs to the controllers. The controllers give the reference current as output, which is fed as input to the current controller. The current controller generates the gate current to the six step inverter based on the comparison between the actual phase current of motor which is sensed by the hall sensor and the reference current from controller. The input voltage of the BLDC motor is controlled by firing angle of the inverter

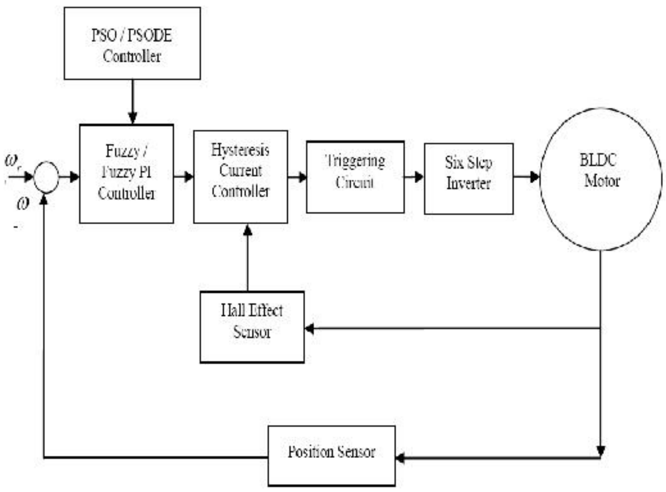

Fig.1 Block Diagram For Speed Control Of BLDC Motor

D. Work carried out on BLDC Motor

Speed control of Brushless DC motor is achieved by four controllers as mentioned above. To control the speed of BLDC motor, a three-phase BLDC motor is fed by a six step voltage inverter. A speed regulator is used to control the DC bus voltage. The inverter gates signals are produced by decoding the Hall Effect signals of the motor. The three-phase output of the inverter is applied to the BLDC motor. Two control loops are used. The inner loop synchronises the inverter gates signals with the electromotive forces. The outer loop controls the motor's speed by varying the DC bus voltage. Initially, a FLC has been developed and implemented for the speed control of the motor in Matlab/Simulink environment.

The inputs to the FLC are speed error and change in speed. Speed error is defined as the difference between the actual speed and reference speed of the motor. Seven membership functions are created for each input and output. The FLC has been built with two inputs and one output. The membership functions are Negative Small, Negative Medium, Negative Big, Zero, Positive Small, Positive Medium, and Positive Big. Based on the values of error and change in error of speed, the output of the FLC is in terms of current. This is the reference value for the current controller. The difference between the reference current from the fuzzy controller and actual armature current is given as an input to the current controller. Based on the current limit, the current controller generates the gate current to the chopper drive. Thus, the speed of the motor is controlled.

In fuzzy PI controller, the gain value is added with speed error and change in speed error. Gain value is used as P and I value of PI controller.

In PSO tuned the fuzzy PI controller, the range of membership functions are tuned to achieve better speed control than fuzzy and fuzzy PI controllers. Each membership function of the inputs and output is considered as a particle. So, the number of particles for the controller is 21. Mean Square Error (MSE) is considered as the fitness function for the PSO algorithm. The minimum of MSE is obtained by using PSO algorithm. The range of membership functions are tuned by PSO, and based on the result of PSO tuning, the range of input and output membership functions are changed to obtain minimum value for the fitness function. MSE is given by,

$$MSE = (y(k) - \overline{y(k)})^2 \tag{5}$$

y(k) is crisp value of actual range of membership function, $\overline{y(k)}$ is the calculated output value of membership function by evaluating the Fuzzy Inference System (FIS) function. After attaining the minimum value of MSE, the corresponding crisp value y(k) gives the new range of values for inputs and output membership functions. The mutation function of DE is implemented in PSO, when the velocity of the PSO is out of the specified range. If the calculated velocity is out of boundary or closely to zero [Velocity < rand(0,1)], a mutation operator of the DE is activated, and the velocity of this particle is recalculated by using mutation operator as,

$$Vi(t+1) = F \times ((xk(t)- xi(t))- (xq(t)- xi(t))) \tag{6}$$

After calculating the velocity using DE mutation operator, the same PSO procedure is carried out for tuning fuzzy membership functions with same objective function.

4. Results And Discussion

A. Varying Speed at No Load Conditions

To demonstrate the system performance of controllers, sudden change of reference speed at no load is introduced. The response due to sudden change of reference speed is illustrated using graphs for various controllers. Performance analysis of the controllers due to sudden change of speed reference is summarized in Table 1 from the graphs shown in Figures 2 and 3. Initially this work focuses on the performance of the all the controllers with no load condition at reference speed 120 rads/sec. From the verification, the settling time of fuzzy logic controller is 0.15 seconds, the fuzzy PI controller is 0.07 seconds, PSO based fuzzy PI controller is 0.035 seconds and PSODE based fuzzy PI controller is 0.03 seconds. When the speed is increased to 200 rads/sec, the settling time of fuzzy logic controller is 0.15 seconds, the fuzzy PI controller is 0.05 seconds, PSO based fuzzy PI controller is 0.025 seconds and PSODE based fuzzy PI controller is 0.02 seconds. From the above comparison, it is proved that PSODE based fuzzy PI controller performs better when compared to the other controllers.

B. Varying Speed at Constant Load

In this condition, speed of the BLDC motor is varied with constant load. Initially the motor is run with 120 rads/sec and then the speed is changed to 200 rads/sec at constant load. Speed response of the BLDC motor is obtained while changing the speed, for all the controllers. With help of Figure 4 and Fig.5, the parameters of speed responses are summarized in Table 2.

From the comparison of the performance of the controllers, the settling time of fuzzy logic controller is 0.20 seconds, fuzzy PI controller is 0.08 seconds, PSO based fuzzy PI controller is 0.035 seconds and PSODE based fuzzy PI controller is 0.032 seconds. When the speed is increased to 200 rads/sec, the settling time of fuzzy logic controller is 0.18 seconds, the fuzzy PI controller is 0.05 seconds, PSO based fuzzy PI controller is 0.03 seconds and PSODE based fuzzy PI controller is 0.025 seconds. From the above verification and comparison, it is proved that proposed PSODE based optimized Fuzzy PI controller gives the better performance in settling when compared to the other controllers.

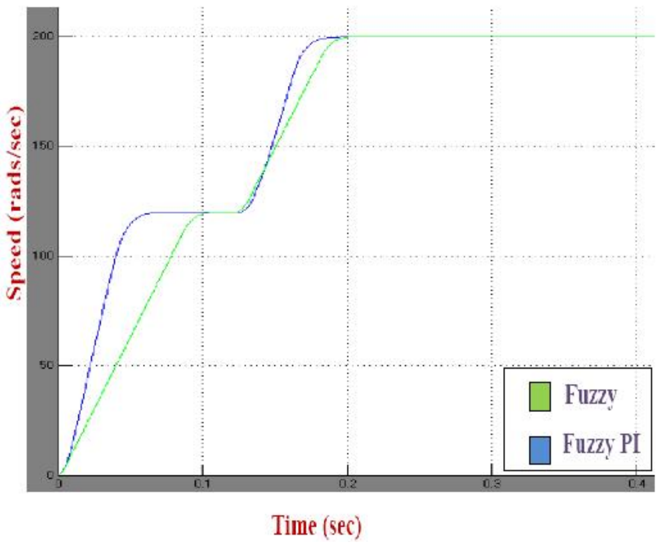

Fig.2 Change In Speed Under No-Load Condition For Fuzzy And Fuzzy PI Controllers

Table 1. Performance Analysis Of BLDC Motor for Sudden Change In Speed At No Load Condition

No Load Condition		Fuzzy	Fuzzy PI	PSO Fuzzy PI	PSO DE Fuzzy PI
At ref Speed 120 rads/sec	OS(%)	-	-	-	-
	t_s (sec)	0.15	0.07	0.035	0.03
Speed Increased to 200 rads/sec	OS(%)	-	-	-	-
	t_s (sec)	0.15	0.05	0.025	0.02

C. Varying Load at Constant Speed

In this criterion, the load is suddenly introduced and released at constant speed. The performances of all the controllers are analyzed at this situation. The speed of the motor is maintained constant at this condition and the load is varied. Initially, no load is applied to the motor. Hence, the motor attains the reference speed and remains in that speed. Speed of the BLDC motor is decreased, when the load is changed from no load to loaded condition and is returned to the reference speed when the load is released. Based on the speed response graphs shown in Fig.6 and Fig.7, the results are summarized in Table 3. From the analysis of the values in Table 3, the setting time of speed response of the BLDC motor with fuzzy PI, PSO fuzzy PI and PSODE fuzzy PI controllers is found to be close to 0.01 seconds. Settling time with FLC is 0.05 seconds. No overshoot occurs in speed response for all the controllers.

D. Varying Speed and Load Simultaneously

Under this condition, both the speed and load of the motor are changed. In this research, two cases are considered, increase in speed with no load, increase in speed and increases in load.

Based on the speed response graphs shown in Figures 8 and 9, the results are summarized in Table 4. Under the sudden change one, settling time of speed response is 0.15 seconds with FLC, 0.07 seconds with fuzzy PI, 0.035 seconds with PSO Fuzzy PI and 0.03 seconds with PSODE fuzzy PI. Under the sudden change two, settling time of speed response is 0.21 seconds with FLC, 0.05 seconds with fuzzy PI, 0.025 seconds with PSO Fuzzy PI and 0.02 seconds with PSODE fuzzy PI. From the performance comparison of the controllers, the hybrid PSODE gives better results than other controllers.

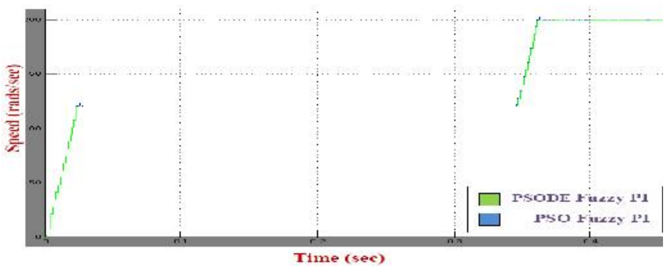

Fig.3 Change In Speed Under No-Load Condition For Pso Fuzzy PI And PSODE Fuzzy PI Controllers

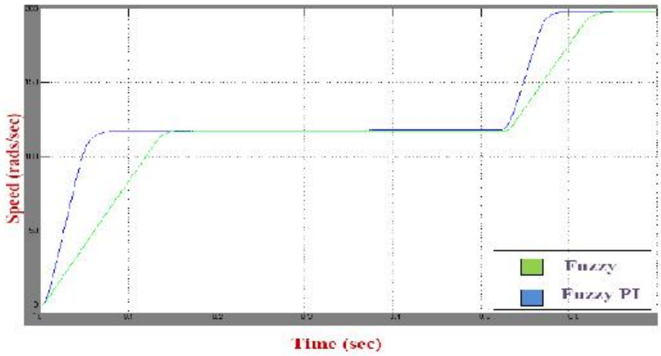

Fig.4 Change In Speed With Constant Load For Fuzzy And Fuzzy PI Controllers

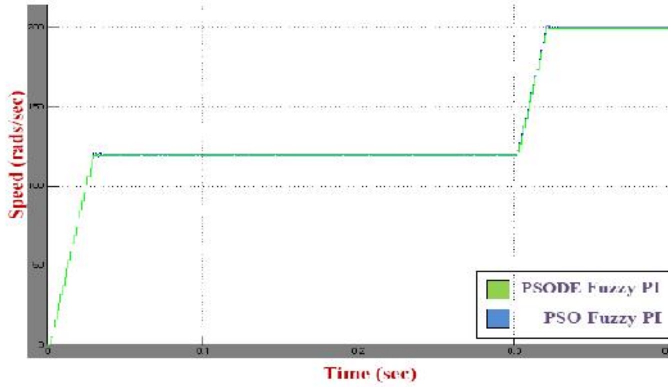

Fig.5 Change In Speed with Constant Load For PSO Fuzzy PI And PSODE Fuzzy PI Controllers

Table 2.
Performance Analysis Of BLDC Motor For Sudden Change In Speed At Load Condition

At load condition		Fuzzy	Fuzzy PI	PSO Fuzzy PI	PSO DE Fuzzy PI
At ref Speed 120 rads/sec	OS(%)	-	-	-	-
	t_s (sec)	0.20	0.08	0.035	0.032
Speed Increased to 200 rads/sec	OS(%)	-	-	-	-
	t_s (sec)	0.18	0.05	0.030	0.025

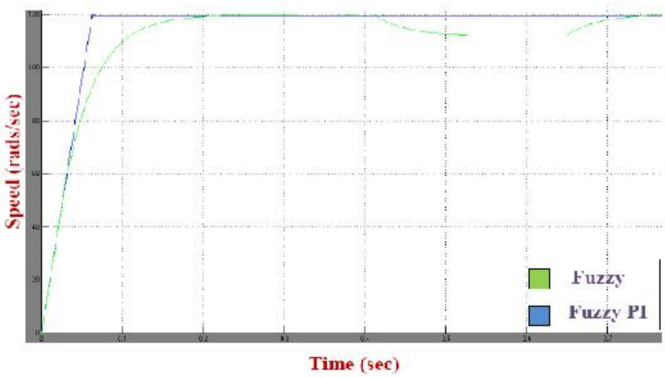

Fig.6 Change In Load With Constant Speed For Fuzzy And Fuzzy PI Controllers

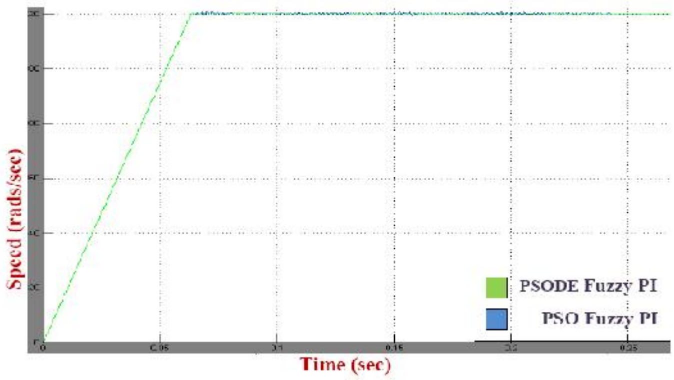

Fig.7 Change In Load With Constant Speed For PSO Fuzzy PI And PSODE Fuzzy PI Controllers

Table 3. Performance Analysis Of BLDC Motor For Sudden Change In Load With Constant Speed

At reference speed 120 rads/sec		Fuzzy	Fuzzy PI	PSO Fuzzy PI	PSO DE Fuzzy PI
At load applied	OS (%)	-	-	-	-
	ts (s)	0.05	0.01	0.01	0.01
At load released	OS (%)	-	-	-	-
	ts (s)	0.05	0.01	0.01	0.01

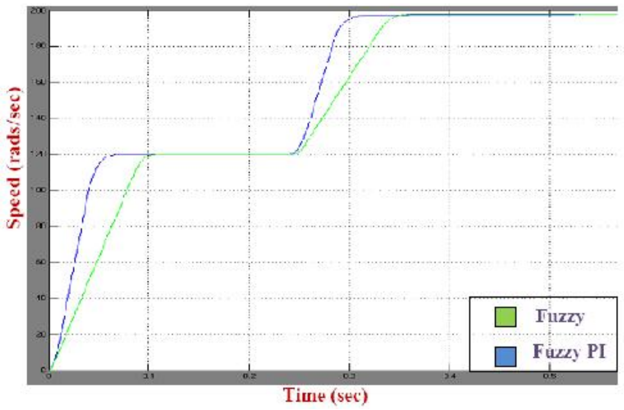

Fig.8 Change In Speed And Load For Fuzzy And Fuzzy PI Controllers

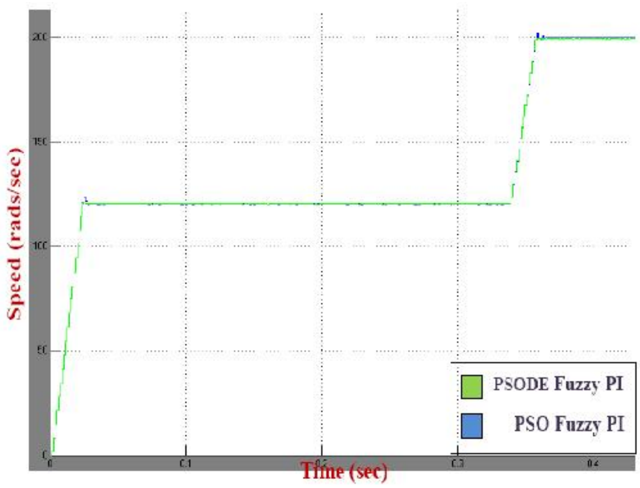

Fig.9 Change In Speed And Load For PSO Fuzzy And PSODE Fuzzy PI Controllers

Table 4. Performance Analysis Of BLDC Motor For Changes In Speed And Load Simultaneously

		Fuzzy	Fuzzy PI	PSO Fuzzy PI	PSO DE Fuzzy PI
Sudden Change 1	OS(%)	-	-	-	-
	t_s (sec)	0.15	0.07	0.035	0.03
Sudden Change 2	OS(%)	-	-	-	-
	t_s (sec)	0.21	0.05	0.025	0.02

5. Motor Parameters

Stator phase resistance (R) – 0.2 Ohms
Stator phase inductance (Lm) – 8.5e-3 Hentry
Flux link established by magnet – 0.175 V-s
Moment of inertia (j) – 0.089 Kg-m2
Fiction co-efficient (B) – 0.005 N-m-s
Number of pole pair – 4
Voltage constant – 146.60
Torque constant – 1.4

6. Conclusion

Four controllers namely, FLC, Fuzzy PI, PSO Fuzzy PI and proposed PSODE-based fuzzy PI controllers are developed and implemented for the speed control of BLDC motor. A comparison of performance has been performed for the proposed hybrid controller with other existing controllers of various types. It has been found that the speed regulation by the proposed hybrid PSODE-Fuzzy PI controller is well above the rated values.

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