An Adaptive Intelligent Sliding Mode Control method for BLDC Motor Using Optimized Fuzzy PID Controller

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Abstract - Brushless DC motor is one type of permanent synchronous motor, which is applied in various industrial and commercial applications. This is because it has number of advantages like high power density, large torque, lifetime, good speed regulation and reliability. However, the controls of effective speed control and current control of brushless DC motor are still difficult. Further, the uncertainty and non-linear characteristics of the motor system degrades the efficiency of controllers. To address and end this difficulty, a novel control scheme is proposed by using optimized tuned parameters with Fuzzy PID controller for the speed control of BLDC motor. Several nature-inspired optimization algorithms like particle swarm and cuckoo search algorithms are developed for controller design. The proposed Fuzzy PID controller design is carried patterned using cuckoo search algorithm for tuning the optimized parameters. The speed of the motor can be tuned depending upon the sliding mode surface parameters. Similarly, Adaptive Intelligent Sliding Mode Controller is designed by using cuckoo search algorithm which employs an inner loop for current control and outer loop as speed control. Here, two cascaded sliding mode controllers taking into account which improves dynamic control of BLDC motor. It is guaranteed that the developed AISMC strategy deals with uncertainty and non-linear characteristics of unknown external disturbance. The precise experimentation was implemented in MATLAB simulation environment, and system performance is analyzed regarding stator current, torque, back EMF, the line to line voltage and settling time of the motor.

Keywords: BLDC motor, Adaptive Intelligent Sliding Mode Controller, Current and Speed control, Optimized Fuzzy PID Controller.

I. INTRODUCTION

There are several sorts of electrical motors which are appealing and utilized as an element of variable speed applications. The demerit of brushed motors is its less effectiveness, which is mainly due to the mechanical characteristics of a commutator, electromagnetic noise of brush flash and also its brush nature. These problems are mitigated by Brushless DC motor, which eliminates the presence of brushes. The initial implementation cost may be more expensive; however, it reduces time complexity during the operation. Brushless DC motors are mostly used in industrial and traction applications which have merits of high torque, large efficiency, less maintenance and low noise.

Among various controllers like P (Proportional), PI (Proportional Integral), PD (Proportional-Derivative) and PID (Proportional Integral Derivative) controllers, PID is an optimum choice for speed control of BLDC motor. It has a lot of advantages compared to others. The comparative analyses of different controllers are briefly discussed in [1]. Yet, tuning of PID controller makes uncertainty in system parameters. In this research work fuzzy PID controller with an optimized algorithm is followed to resolve this problem. Compared to traditional controllers, fuzzy controllers facilitate better outcomes. These are adaptable to the non-linearity systems with different loads and speed variations. For that purpose, the results of sliding mode controller are adapted to system uncertainties.

Sliding mode control (SMC) is a non-linear control technique which modifies the dynamic nature of a system. The discontinuous signal is a set-valued signal which forces the system "slide" along with a cross-section of normal behavior of the system. For that, state-feedback control method has been introduced. Based on the current position in state space, it switches from one continuous structure to another. Therefore, SMC is one kind of variable structure control method. This control structure method is designed in such a way that trajectories are moved towards an adjacent region. The ultimate trajectory will slide along the boundaries which are called as a sliding mode, while the boundaries in geometrical locus are called as sliding or hyper surface.

The sliding mode control utilizes infinite gain in order to force trajectories of a system to slide along with restricted sliding surface. The system slides along the surface until it reaches its equilibrium state. Although the control law is not a continuous function, the sliding mode must be reached within a finite time, which means that it is better than its asymptotic behavior. Therefore, the sliding mode controller is one of the optimal controllers applied in a broad set of dynamic non-linear systems. Ramya et al [2] proposed a self-tuned fuzzy PID controller for BLDC motor in the presence of external disturbances. This self-tuning approach combines both PID controller at steady state and fuzzy PID tuned controller at transient response. Sumardi et al [3] presented a self-tuned fuzzy PID controller, embedded in ATMega microcontroller in order to control the speed of the BLDC motor. In section II, several sliding mode controllers of BLDC motor are briefly explained.

II. RELATED WORKS

The sliding mode control (SMC) is a familiar control strategy which deals with a non-linear uncertain system. Various control techniques have been designed for improving the speed and current control of BLDC motor. As a result, online Adaptive Neuro-Fuzzy interference system is designed which uses Bat algorithm. Learning parameters such as learning rate, steepest descent momentum constant and forgetting factor are fed to the system optimization **[4]**. Finite time convergence global sliding mode control scheme was introduced in the paper **[5]**. Their control strategy is performed in second-order multiple models communication systems.

Optimization techniques employ a significant role to resolve optimization problem. The results of the optimization process are either maximum or minimum and the result is called as an objective function **[6]**. The Cuckoo search algorithm is a nature-inspired algorithm **[7]** which is mainly used for solving the optimization problem in various engineering fields. It is a global optimization method which maintains the balance between local and global using switching parameters. The continuous function designed parameters are fixed which resulted in degrading the efficiency of the system. To resolve this continuous function problem, **[8]** proposed an adaptive cuckoo search (ACS) used to properly tune the parameters. Unlike original cuckoo algorithm, this proposed method facilitates enhanced convergence rate and high accuracy.

It also eliminates the structural engineering problems. For this purpose, **[9]** presented an adaptive cuckoo search algorithm (ACSA) which an adaptive step size selection strategy for the diversification process. Through this strategy, convergence characteristics keep the balance between intensification and diversification. Various types of cuckoo search algorithm are introduced for solving economic load dispatch problem, secured vehicle ad-hoc network, optimum feature selection and antenna arrays **[10]**. **Galphade et al [11]** implemented an SMC scheme, obtaining ripple free torque via inner loop current control that is done by effective speed tracking. Here, two first order sliding controllers have been designed, which is based on reaching law algorithm; one is the inner current loop control and another is the outer speed loop control of the drive. It is a robust sliding mode scheme which obtains a reduction of settling time, steady-state error and disturbance rejection.

Generally, PI controller is used for switched reluctance motor and its main drawback is the requirement of high overshoot and huge settling time. This hitch or hindrance occurs due to the fixed nature of parameters used by the controller. It produces poor performance at sudden changes in reference speed and load. To mitigate this problem, **Arun Prasad et al [12]** presented a Fuzzy Sliding Mode Controller (FSMC) which integrates fuzzy interference system with sliding mode controller. The proposed mathematical modeling of 6/4 switched reluctance motor improves speed efficiency of motor and speed response is increased when Fuzzy SMC is utilized. Thus, peak overshoot is effectively eliminated and also rising and settling time have been improved by using Fuzzy SMC for switched reluctance motor. Permanent magnet brushless DC motor is used widely in industrial applications due to its ease of control. From conventional PI and PID controller, Fuzzy based controller is a popular one to optimize the speed control of the motor. **Simon Darsingh et al [13]** suggested an intelligent Adaptive Neuro-Fuzzy Interference system (ANFIS) to achieve optimized speed control response of motor using cuckoo search optimization technique. Through their simulation results, they assured that the proposed optimized algorithm was able to diminish undershoot and overshoot problems and achieve high speed response.

Monteiro et al [14] proposed an analog switching function based sliding mode control method for controlling BLDC motor. The ultimate aim of this work is reducing input chattering. This denoted that for speed control, electromagnetic torque is used as the reference and for the current loop, PWM cycle is utilized. The SMC topology is applied in both mechanical speed control and stator current loop control. Without the requirement of fine-tuning of controller parameters, this technique attains good chattering reduction and robustness even in the disturbance environment. The main advantage of this method is in place of a signal function, hyperbolic tangent has been used for SMC topology that improves motor robustness. The main disadvantage is the occurrence of a steady state error in shaft speed. However, depending upon the nature of applications low value of steady-state error can be obtained.

Reaction flywheel is one of the significant actuators that can be used for satellites attitude control which requires high torque and rotation speed. **Liu Gang et al [15]** presented a novel approach in order to improve the required constraints. The topology of reaction flywheel is implemented first and small signal linearization process for buck-boost converter. The general SMC performances are analyzed by Lee derivation based on state averaging model and reaching qualification. Various sliding surfaces are selected during electro-motion, energy consumption braking and reverse connection braking stages. **Muhammad et al [16]** introduced a two-step linear matrix inequalities (LMI) approach for sliding mode control of BLDC motor. This approach is a method of designing a controller which provides extreme stability of closed loop system using the concept of lyapunov. It shall be assumed that BLDC motor system model is to be a linear continuous time-invariant type. The proposed approach is implemented in MATLAB LMI solver tool in order to resolve inequalities of a matrix. A tachometer is used as a feedback sensor **which is** driven by an inverter. For communication, Arduino has to be connected via computer which controls the tachometer. However, due to high frequency switching process of the motor, a chattering problem was occurred.

Mirela Dobra et al [17] presented a mathematically matching the sliding mode controller with BLDC permanent magnets (BLDC-PM). It shall be assumed that the BLDC-PM motor system has additive uncertainty under load torque variation through which the speed of the motor can be tested. The motor drive control loop implementation utilizes TMS320F28335 microcontroller using some additional facilities for electric signals. The ultimate goal is setting up the speed and position of the motor via a velocity control loop system. **Bharathi et al [18]** proposed a permanent magnet BLDC (PMBDC) motor, based on sliding mode reaching law. Provis**ion o**f a drive system to the motor is used to make adjustable speed control applications. The entire process is implemented in MATLAB/ Simulink environment and the motor speed is controlled by varying the frequency of pulses depending on signal feedback. The signals are generated from Hall effect sensors. Through the Simulink results, it is confirmed that the proposed PMBLDC has better control performance and speed control when compared to the conventional PI controller.

Lack of frameworks and non-linear characteristics of BLDC motor degrade the execution of controllers. Those problems, ignored by sliding mode controller have to be utilized; however, it is affected by the chattering problem in motor driver. **Vimal Nigam et al [19]** presented a hybrid fuzzy sliding mode controller for reducing the chattering problem of BDLC motor. The fuzzy controller, which is used as an internal feedback circle, closes the controller and diminishes the chattering. Through fuzzy controller, the motor is able to achieve a swell- free stator current and less torque throb. It can also be applied in the dynamic drive system and non-direct loads. A discrete time sliding mode inventory management depends on non-switching type reaching law which is introduced in **[20]**. The sliding variable rate change is upper bound in order to design the system initial conditions. **Pawel Latosinski et al [21]** developed a reaching law for continuous and discrete time system. Also, the switching type and non-switching type of discrete reaching laws are elaborated. The proposed approach follows observer-control strategy **[22 and 23]** which could assure better performance when compared to traditional Fuzzy Sliding mode controllers.

III. MOTIVATION AND PROBLEM FORMULATION

A Sliding Mode Controller has robust features which able to deal with non-linear characteristics of the motor. The proposed approach is a voltage controller to adapt the type of loads or magnitude variations of load. BLDC motor is employed in a variety of applications due to its advantages such as high torque, low inertia, high efficiency and quick response. Basically, dynamic response, less power consumption, higher steady precision and capability for handling interference are necessary for motor speed regulation system. Therefore, a reliable and powerful control strategy is needed for BLDC motor. In order to meet these motor requirements, Fuzzy PID controller with sliding mode control strategy is employed in this work. In addition to optimization, a cuckoo search algorithm is applied for tuning the surface parameters. From that, it can control the speed and current produced by the motor. This results in the disturbance rejected output to achieve a good dynamic response.

IV. SLIDING MODE CONTROLLER

In BLDC motor, the inner current loop and outer speed control can be done by utilizing a technique called exponential reaching law. Typically, Sliding Mode Control is one of the familiar non-linear control techniques, which has the capability of changing system performance continuously. According to the known current status of the system state, switching the controlled variables continuously. Hence, it causes a trajectory towards moving on a pre-defined sliding surface area. The following Figure 1 shows a sliding mode representation of the phase trajectory with two modes of the system.

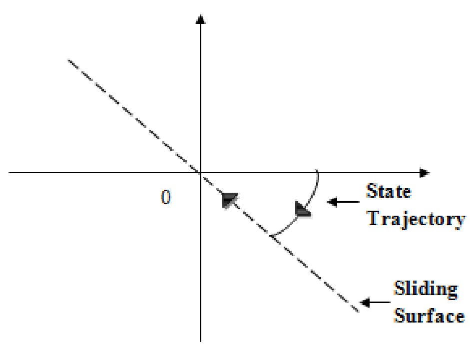


Fig.1. Representation of sliding motion in phase

In Mode 1, the phase plane moves towards the sliding surface, whereas the trajectory point starts from anywhere on it and finally reaches the surface at a finite time. The entire process is known as reaching, non-sliding phase or hitting. The system becomes very sensitive to variations in parameter and also a rejection of disturbance is a part of phase trajectory. On the other hand, in Mode 2, sliding phase in which state trajectory moves to origin along with sliding surface. And state trajectory does not leave the sliding surface. During that time, the system is independent of its parameters and external disturbances.

The design of sliding mode involves in two processes. In the state space, the desired stability of the system decides which kind of state trajectory is to be used. Also, selected trajectory must lie in the state space. An effective control law makes the sliding surface as most attractive for state trajectory and helps to reach in a finite time.

Usually, the sliding surface may be either linear or non-linear. For convenience, a linear sliding surface can be used. When the origins of coordinate's axes are taken, the system turns to the stable equilibrium state. Then, the main objective is to force the trajectory on to the sliding surface which is denoted by "S" and it should move towards the origin. The basic concept behind Sliding Mode Controller is to define a surface along which process will slide to its desired finite value. The mathematical model of the sliding mode controller is illustrated below.

Mathematical model of Sliding Mode Controller

Generally, according to prescribed control law, the structure of the controller is intentionally modified as its state crosses the surface. First, the sliding surface to sliding mode controller is defined, which is denoted as s (t). It is selected in order to represent a desired global behavior for system stability and tracking performance. The ultimate objective of control mechanisms is ensuring that control variable to be equal to its reference value at all time or not. This indicates the error denoted by e (t) and also its derivative should be zero. After reaching the reference value, it points out that sliding surface s(t) will meet its constant value. In order to maintain and keep s (t) at this constant value, the error e (t) must be zero at all times. The desired surface area is given in Equation (1).

$$\dot{S} = \frac{ds(t)}{dt} \text{ --------------- } \textbf{(1)}$$

$$\dot{S} = \frac{d(\text{Constant})}{dt} = 0 \text{ --------------- } \textbf{(2)}$$

After selecting a sliding surface the control law is implemented, which derives the controlled variable to its reference value.

The general equation for calculating sliding surface is suggested by **Slotine [21]** et al used to confirm variable convergence towards the desired value. The Sliding surface tracking equation can be expressed in Equation (3) is given below.

$$S = \left(\alpha + \frac{d}{dt}\right)^{n-1} e \text{ --------------- } \textbf{(3)}$$

Where, n → order of the system

e→ Generated error signal

α → Constant

By considering the Equation (4) and Equation (5), the motor control loops such as the current loop and speed loop can be controlled.

$$S1 = e1 = i_{reference} - i \text{ ---------- } \textbf{(4)}$$

And

$$S2 = e2 = \omega_{reference} - \omega \text{ --------- } \textbf{(5)}$$

Where, $i_{reference}$ → Reference current value and

$\omega_{reference}$ → Reference speed value.

By employing reaching law, motor speed loop and the current loop can be controlled and control law can satisfy the following reaching condition which is given as

$$S\dot{S} < 0 \text{ --------------- } \textbf{(6)}$$

To satisfy the above condition, reaching law is well suited in this case. The basic representation of reaching law is defined as

$$\dot{S} = -\epsilon sgn(s) - KS \text{ --------------- } \mathbf{(7)}$$

Here, ϵ and K are positive constants called as hitting control gain parameter,

S→ Sliding surface and

Sgn → Signum function

The Signum function is otherwise called as sgn function is defined as

$$Sgn = \begin{cases} 1 & if\ S > 0 \\ -1 & if\ S < 0 \end{cases} \text{ --------------- } \mathbf{(8)}$$

The inner current loop is stated as

$$\dot{S1} = -\alpha sgn(S1) - \beta S1, \text{ then}$$

$$\dot{S1} = \frac{de_1}{dt} \text{ --------------- } \mathbf{(9)}$$

Substitute Equation (4) in Equation (9). We get,

$$\frac{de_1}{dt} = \frac{d(i_{reference})}{dt} = -\alpha sgn(S1) - \beta S1 \text{ -- } \mathbf{(10)}$$

$$\frac{di_{reference}}{dt} - \frac{di}{dt} = \frac{V - iR - E}{L} = -\alpha sgn(S1) - \beta S1 \text{ --------------- } \mathbf{(10)}$$

Using Equation (10) and Equation (4)

$$V = L\left(\propto sgn(S1) + \beta S1 + \frac{di_{reference}}{dt}\right) + E + \left(i_{reference} - i\right)R \text{ ------ } \mathbf{(11)}$$

Similarly, the outer speed loop can be calculated as

$$\dot{S2} = -\gamma sgn(S2) - \zeta S2 \text{--------- } \mathbf{(12)}$$

$$\frac{de_2}{dt} = \frac{d(\omega_{reference} - \omega)}{dt} = -\gamma sgn(S2) - \zeta\ S2 \text{ --------------- } \mathbf{(13)}$$

$$\frac{d\omega_{reference}}{dt} + \frac{(B\omega - T + T_L)}{J} = -\gamma sgn(S2) - \zeta\ S2 \text{ --------------- } \mathbf{(14)}$$

Using Equation (13) and Equation (5)

$$T = J\left(\gamma sgn(S2) + \zeta\, S2 + \frac{d\omega_{reference}}{dt}\right) + T_L + \left(\omega_{reference} - \omega\right)B \text{ --- } \mathbf{(15)}$$

From the derivation, Equation (11) and Equation (15) represents current and speed control loop equations respectively.

The block diagram illustration of the sliding mode controller (SMC) is shown in Figure 2. From the diagram, it is known that there are two controllers, one for controlling the current loop while other for speed control loop of BLDC motor. The speed slip of the motor is minimized at the external loop. This can be done by changing gamma and zeta parameters and finally reaching the desired motor's speed. The output of the first controller is fed as input into the second controller that is intended for current control. The inner loop current lapse is controlled and minimized by the consistent shifting of positive constants alpha and beta. Hence, desired motor current and control mechanism are achieved.

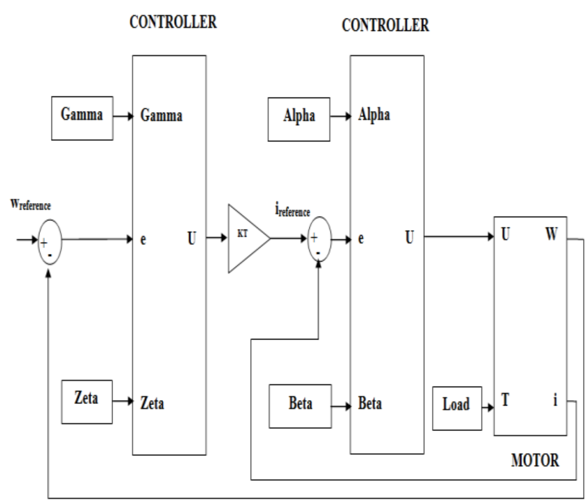


Fig.2. Block Diagram of Sliding Mode Controller

However, handling of slide controller parameters causes difficulty at under critical situation. In order to provide an optimal solution, a cuckoo search algorithm is designed for tuning sliding parameters values as desired. Many optimal solutions have been found in the field of engineering whose objective functions are highly non-linear and non-differentiable. A new meta-heuristic search algorithm called cuckoo search algorithm is first proposed by Yang and Deb in 2009 **[24]**.

V. PROPOSED METHODOLOGIES

Fuzzy PID controller design and optimization

The optimization design of Fuzzy PID controller for BLDC motor speed using cuckoo search algorithm is illustrated in Figure 2. The objective function is set from sum squared error between I(s) and C(s) and it is given in Equation (16). The proposed Fuzzy PID controller is designed in such a way that, to search optimal parameters Kp, Ki, and Kd. The objective is again fed back and fed as input to CS block to minimize and find optimal parameters of the controller. The objective function of the designed controller is given below.

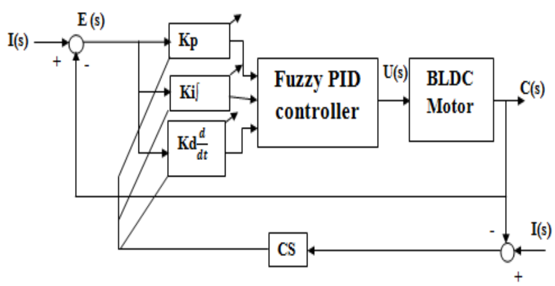


Figure.3. CS-based optimized Fuzzy PID controller

From Figure 3, the Fuzzy PID controller has three inputs such as proportional error, integral error and derivative error. The transfer function of the fuzzy PID controller is given by

$$U(s) = K\left(1 + \frac{1}{T_I s} + T_D s\right) \text{---------} (16)$$

Where K is a proportional gain,

K_I is integral gain,

K_D is derivative gain.

T_I is integral time constant

T_D is the derivative time constant.

The proportional term is providing total gain of its control actions. The integral term is reducing steady state error via frequency compensation by an integrator. The derivative term is increasing transient response and differentiator is used for high-frequency compensation. The control structure of the fuzzy logic scheme is shown in below Figure 4.

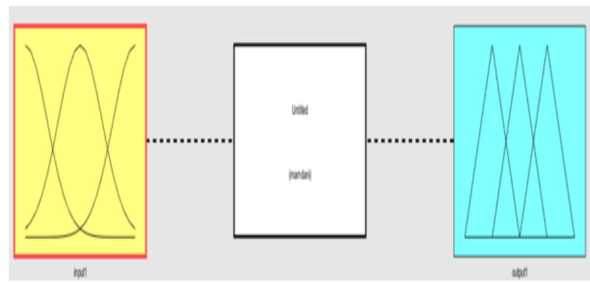


Figure4. Fuzzy Logic Controller system

(i) Fuzzification

The fuzzification is the process of converting input data from suitable linguistic variables. During this process, real inputs are converted into fuzzy values by using suitable triangular membership functions. Then, numbers of logical statement called fuzzy rules are in IF-THEN statements. The fuzzy rules are derived from the number of membership functions. Next, fuzzy outputs are converted back into real inputs at a de-fuzzification process. From Figure 5, it can be observed that there are two inputs namely, speed and change of speed signal given to the controller. Consider the implemented system under the universe of discourse and for both the inputs are normalized from [-1, 1]. The linguistic labels are called Big negative, Small negative, Zero, Small positive, Big positive and output linguistic variables are represented as BN, SN, Z, SP, BP.

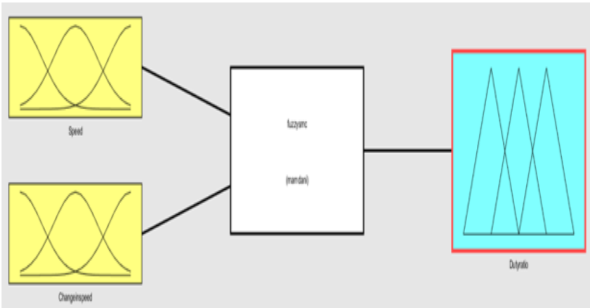
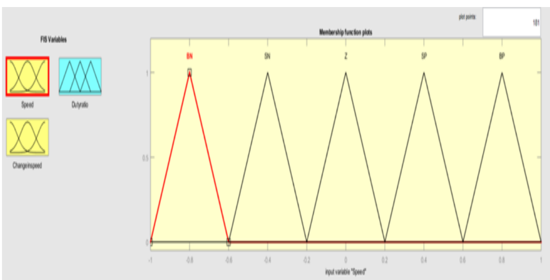
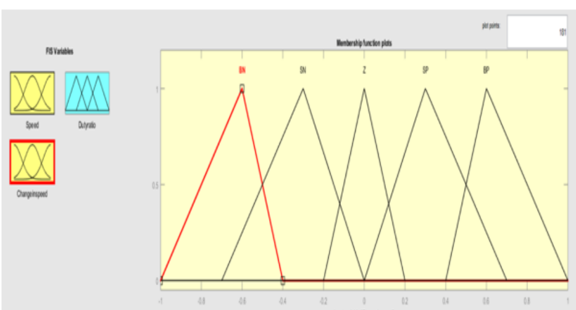


Figure5. Input and Output of fuzzy logic controller

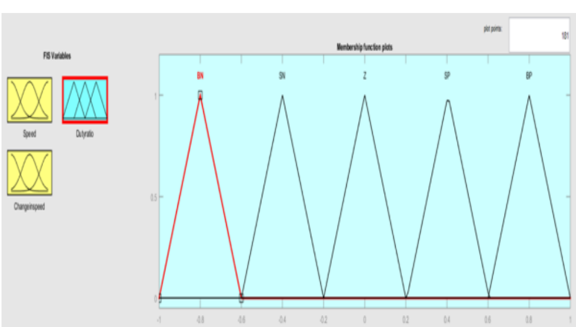
The following Figure 6 shows triangular membership functions (a) input-1 speed, (b) input-2 change in speed and (c) membership functions of output respectively.



6(a) Membership Function of input-1 speed



6(b) Membership Function of input-2 change in speed



6(c) Membership Function of output variable

Fig.6. Representation of Membership functions

(ii) Rule base

Based on the knowledge of control rules and linguistic variables, fuzzy control strategy follows IF-THEN statement in order to make the decision. The rule base is defined by means of speed and change of speed linguistic labels. Consider the input speed and change in speed has 5 linguistic labels and change in speed has 5 linguistic labels. Hence, totally 5 X 5=25 rule base are given in Table 1.

Speed/ Change in speed	BN	SN	Z	SP	BP
BN	BP	SN	SP	SN	SP
SN	SP	Z	SP	BP	BN
Z	SN	SP	SP	BN	SP
SP	SN	BP	BN	BN	SP
BP	SP	BN	SP	SP	BP

Table1. Rule Base of Fuzzy logic

(iii) De-fuzzification

The De-fuzzification is the reverse process of fuzzification which yields real input data from the fuzzy output. Commonly, a center of gravity or center of an area has to be followed for this process.

Overview of cuckoo search algorithm

In a cuckoo search algorithm, each egg in a nest denotes a solution while cuckoo egg represents a new optimal solution. Generally, the following three constraints are followed in their algorithm:

1. Only one egg has been laid by each cuckoo at a time. Then, eggs are dumped into the nest and selection will be done randomly.

2. The High quality eggs (solutions) from the nest are taken to next generations.

3. The numbers of hosts' nests are fixed and each host discovers only one alien egg with a probability. In this case, a host can either throw the egg away or rebuild a new optimal solution.

The initial objective function is given in Equation (16)

$$\mathbf{x} = (\mathbf{x_1}, \mathbf{x_2}, \dots \dots \mathbf{x_d})^{\mathbf{T}} \text{ ---------- } \mathbf{(16)}$$

And initial population of n hosts is $x_i(i = 1,2, \dots . n)$.

When generating a new solution, x_i (t+1) for cuckoo i and t is current generated solution and then performing Levy flight approach. It is given by

$$\boldsymbol{x_i(t+1) = x_i(t) + \propto \oplus} \textbf{ Levy } (\boldsymbol{\lambda}) \textbf{ - (17)}$$

A levy flight approach which is a random walk, whose step lengths are drawn from a Levy distribution function in Equation (18).

$$\boldsymbol{Levy\ u = t^{-\lambda}} \text{ --------------- } \mathbf{(18)}\ \mathbf{;} \text{ Where, } 1 < \lambda \leq \text{n.}$$

However, cuckoo search algorithm has limited advantages, since $\lambda$and$\propto$ affect global and local research of cuckoo search algorithm. To mitigate this problem, adaptive intelligent cuckoo search algorithm (AICSA) is proposed. The flowchart for cuckoo search algorithm is shown in below Figure 7.

Table 2.Parameters of BLDC motor

S.No	Parameter	Specification
1	Motor's speed	3000 rpm
2	Voltage constant	51.8307 Vpeak L-L/krpm
3	Torque constant	0.428636 N.m/Apeak
4	Resistance per phase	0.18 ohm
5	Inductance	0.00167 H
6	Moment of inertia	0.000621417 J(kg.m^2)
7	Friction factor	0.000303448 F(N.m.s)
8	Pole pairs	4

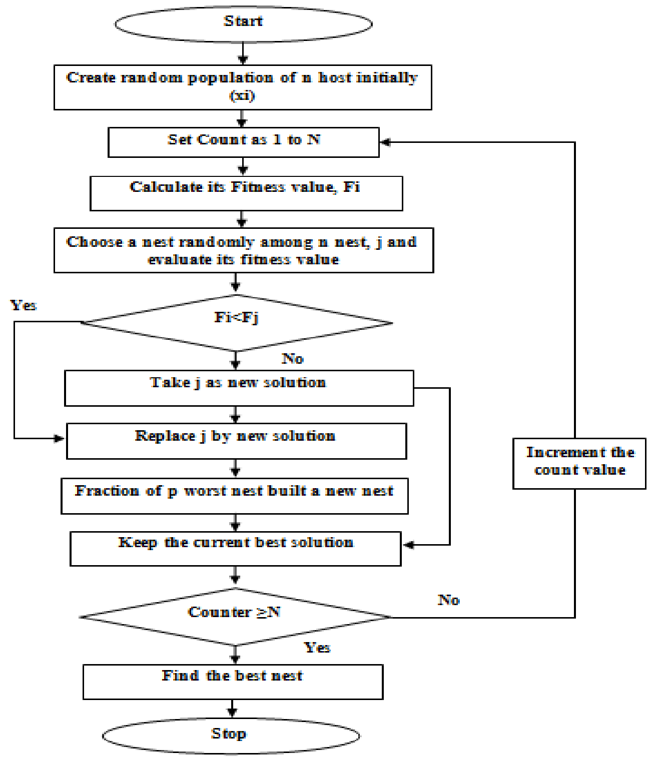


Fig.7. Flow diagram for cuckoo search algorithm

Levy flight method is a random process, selection of step size will causing lack of adaptation. The step size is not a fixed one, sometimes it may be large or sometimes may small. For a globally optimized solution requires a large step-length. The main difference between AICSA and cuckoo algorithm is a way of adjusting the parameter with self-adaptation ability. The optimum value of parameters Gamma (γ), Zeta (ζ), Alpha (α) and Beta (β) can be achieved by using the AICSA algorithm.

The fitness function of AICSA is given by

Fitness function,

$$\boldsymbol{F_i = Min[e_i]} \text{ --------------- } \mathbf{(19)}$$

Where, i=1, 2, 3……n.

e_i represents i^{th} sample trajectory error function.

The generated new solution with Levy flight is given in the following Equation (20).

$$x_i^{t+1} = x_i^t + \propto \oplus \textbf{Levy}\ (\boldsymbol{\lambda}) \text{ --------------- } \textbf{(20)}$$

Where ∝ is called as step size which is greater than one. It is measured by

$$\propto = \boldsymbol{random} * \boldsymbol{step} \text{ --------------- } \textbf{(21)}$$

$$\boldsymbol{Step} = \frac{\boldsymbol{U}}{\boldsymbol{V}^{1/\boldsymbol{\beta}}} \text{ --------------- } \textbf{(22)}$$

$$\boldsymbol{U} = \boldsymbol{N} * \boldsymbol{\sigma} \text{ And } \boldsymbol{V} = \boldsymbol{N} \text{ --------------- } \textbf{(23)}$$

And

$$\boldsymbol{\sigma} = \left[\frac{\gamma(1+\beta) sin\left(\frac{\pi*\beta}{2}\right)}{\gamma\left(\frac{1+\beta}{2}\right)*(\beta)*\left(2^{\frac{\beta-1}{2}}\right)} \right] \text{ --------------- } \textbf{(24)}$$

Where γ, β are random values as ranging from 0 to 1.

The Random walk via Levy flight having a capability of investigating searching up to step length may be any longer. And the levy flight random step length is given by

$$\boldsymbol{Levy} \approx \boldsymbol{u} = \boldsymbol{1^{-\lambda}}, \boldsymbol{1} < \boldsymbol{\lambda} \leq \boldsymbol{3}. \text{ --------------- } \textbf{(25)}$$

The sequential jump or steps of the optimal solution can be done through random walk process of Levy flight algorithm and also implies with a power law distribution with an overwhelming tail.

VI. SIMULATION RESULTS

The parameters and their specified values used in the modeling of BLDC motor is listed in the following Table 2.

Figure 8 shows the adaptive Fuzzy PID sliding mode controller for BLDC motor by MATLAB Simulink. The BLDC motor is run at the speed rate of 3000 revolutions per minute. The speed and current of the motor can be controlled by Fuzzy logic with cuckoo search algorithm for selecting optimized parameters. Compared to conventional PID controller, Fuzzy PID controller facilitates better speed regulation of motor. The change of speed is given back as an input into a fuzzy controller, in which the speed can be calculated by comparing reference speed with actual speed. Optimized data is selected by the cuckoo search algorithm among the several input data,. This results that it can control the speed of BLDC motor. The simulation results are carried out to evaluate the performance of BLDC motor in terms of stator current, back EMF, torque and etc.

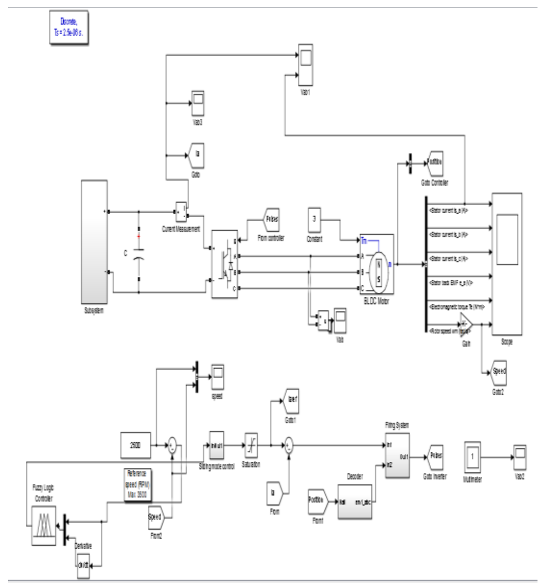


Fig.8.Matlab simulation of BLDC motor control using adaptive Fuzzy sliding mode Controller

Usually, the speed of the motor could vary at different loads. Due to initial phase back EMF; the phase current becomes zero initially. The phase current increases gradually after the motor speed reaches the reference speed, three stator currents variations are represented in Figure 9. The speed response of BLDC motor of fuzzy PID controller is faster than a conventional controller. The result confirms the speed response of the motor and confirms that the fuzzy based controllers will be helpful in many industrial applications. Further, torque response of BLDC motor has considerably reduced the torque ripples. Figure 10 represents the DC voltage and the stator current of BLDC motor.

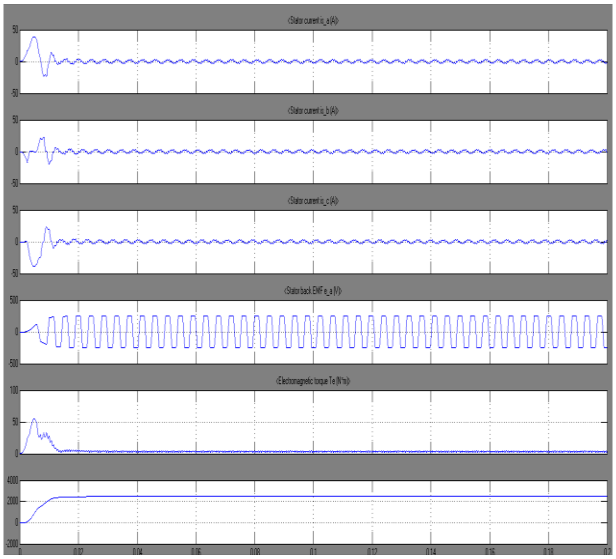


Fig.9.Stator current, Stator back EMF, Electromagnetic Torque and Speed of BLDC motor

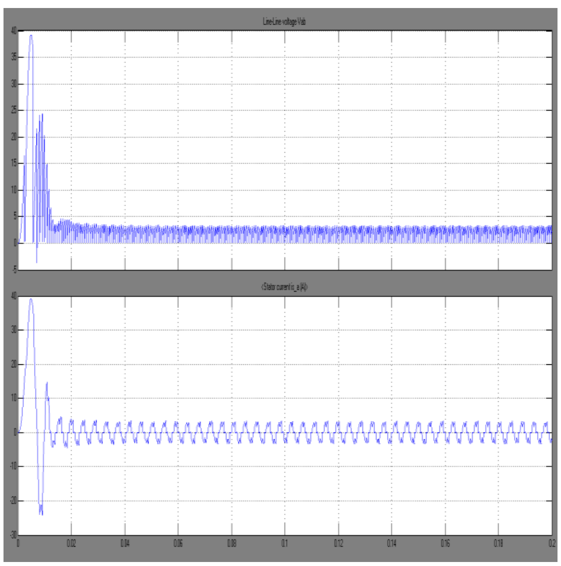


Fig.10.DC voltage and stator current of BLDC motor

Next, the reference speed of BLDC motor is compared with actual speed is illustrated in the Figure 11.

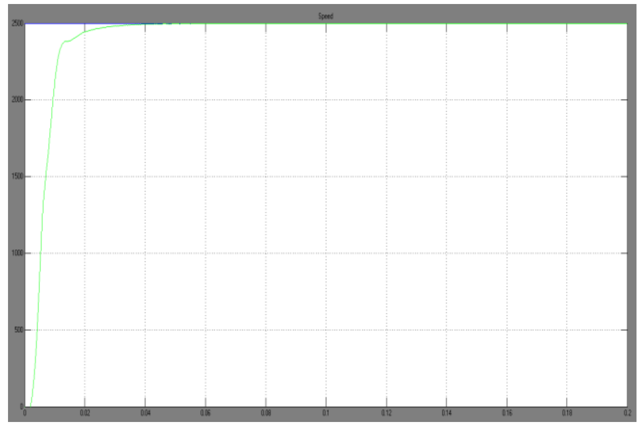


Fig.11.Reference speed Vs actual speed attainment of BLDC motor using fuzzy logic controller

The Figure 12 shows the line to line voltage of BLDC motor and Figure 13 shows line to line voltage at inverter of BLDC motor respectively.

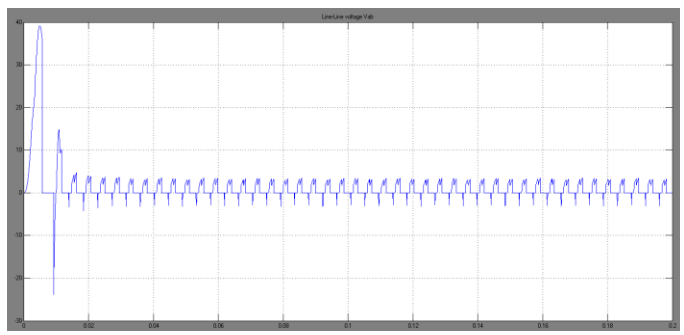


Fig.12.Line to line voltage of BLDC motor

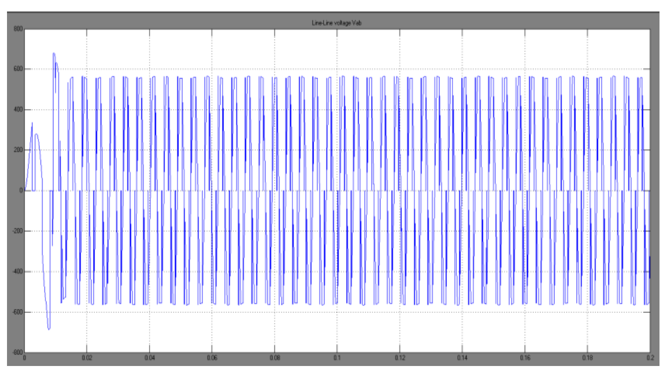


Fig.13. Line to line voltage inverter side of BLDC motor

The performance of proposed methodology is Compared with conventional sliding mode control method of BLDC motor [11] is given in Table 3.

Parameter	SMC [11]	Proposed method
Error(Speed)	0.0248	0.0185
Error(Current)	0.1403	0.1276
Current settling time (s)	0.185	0.176
Speed settling time (s)	0.195	0.166

Table3. Comparison of proposed method with sliding mode controller [11]

VII. CONCLUSION

The BLDC motor is one of* the important applications in the industrial field. The performance of the motor could be degraded due to its uncertain and non-linear characteristics. Since conventional PID controller implementation is simple in its design, it provides moderate performance in disturbed conditions like the change of load and reference speed. In order to control the speed and the current of motor, adaptive fuzzy PID controller is presented in this research work. This approach integrates both advantages of fuzzy logic and sliding mode technique. The Sliding mode control strategy is helpful for effective speed and current control of BLDC motor. In addition to the optimal input data, the control parameters are selected by applying optimized cuckoo search algorithm. The overall experimental system was simulated in MATLAB Simulink environment. From the simulation results, the performance of motor was analyzed in terms of stator current, torque, back EMF line to line voltage and settling time.

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