Hybrid Self Tuned Fuzzy PID controller for speed control of Brushless DC Motor

The objective of the proposed work is to investigate the performance of hybrid self tuned fuzzy proportional integral derivative (STFPID) controller for brushless DC (BLDC) motor drive. The proposed hybrid STFPID controller includes a proportional integral derivative (PID) controller at steady state, a PID type self tuned fuzzy logic (FL) controller (STFLC) at transient state thereby combining the merits of both the controllers. The switching function incorporated in the controller ensures desired control response at various operating conditions by appropriately switching between PID and STFPID based on speed error. A detailed simulation study and performance comparison with other control approaches is performed to highlight the merits of the proposed work. The simulation results indicate that the proposed controller is robust with fast tracking capability and less steady state error. The experimental results are provided to validate the simulation study.

Key words: BLDC motor drive, speed control, self tuned fuzzy logic controller, Hybrid controller, PID controller.
ence of disturbances. In [10], the authors have proposed a robust $H_\infty$ controller design for linear synchronous motor drive. The proposed $H_\infty$ control system has improved tracking performance in comparison to the conventional control system with good dynamic response and robustness. Eventhough a considerable progress has been made in terms of designing $H_\infty$ optimal controllers, design complications are still the main problem in $H_\infty$ controller. Complex mathematical computations of SMC and $H_\infty$ controllers have opened up new avenue for researchers to experiment the design and analysis of controllers for electric drive applications based on artificial intelligence (AI) techniques.

AI techniques based on FL approach, proposed by Lotfi A. Zadeh [11], which is highly effective in controlling non-linear systems does not require mathematical model of the plant and it is based on only linguistic rules. In recent years, researchers have highly focused on different techniques to enhance the performance of FL controller. A novel nonlinear model predictive controller (MPC) based on Takagi-Sugeno fuzzy model, has been proposed for electric vehicle applications[12].The merits of the approach are highlighted by comparing the results of the proposed approach with those of the conventional MPC controller and the optimal fuzzy PI controller. A similar approach based on time varying PI controller based Type 2 FL for speed control of electric vehicle was proposed in [13], in order to get an optimal performance and reduced computation complexity. An intelligent robust PI adaptive control strategy for speed control of Electric vehicles is reported in the literature [14]. This method uses least squares support vectors regression [LS-SVR] for handling dynamic variations of the plant. A self tuning load frequency control strategy for microgrids using human brain emotional learning has been proposed in [15]. Here the emotional controller with the self tuning has a better performance with higher accuracy than conventional controllers. Based on self adaptive modified bat algorithm, a new intelligent online fuzzy tuning approach for multi-area load frequency control is presented in [16], which guarantees the robustness and stability against uncertainties caused by external disturbances. K. Premkumar et al proposed the fuzzy PID supervised online adaptive neural fuzzy inference systems (ANFIS) based speed controller for brushless dc motor [17]. In this paper, the speed control based on different online ANFIS methods is compared and the control system parameters are measured to verify the effectiveness of the controller. An adaptive fuzzy neural network controller for minimizing torque ripple is presented in [18]. A design technique for adaptive deadbeat PI current and speed controllers of BLDC motor drives using particle swarm optimization and ANFIS paradigms is presented in [19]. In addition to conventional fuzzy and neuro fuzzy systems, self tuned fuzzy approaches have been proposed to have feasible control in the presence of load and parameter variations. Self tuning control method provides a promising way of realizing an ideal controller for the problems of uncertainties caused by external disturbances in the plant [20].

It is in this perspective this paper highlights the application and merits of STFPID controller for the control of BLDC motor. With the objective of designing a robust and adaptable controller, this work combines the merits of conventional PID control and self tuned fuzzy approach. The merits of the proposed controller are analyzed in terms of steady state and transient conditions. The proposed paper is organized as follows: The BLDC motor drive system is presented in section 2. The design of self tuned FL controller is discussed in section 3. Section 4 discusses the proposed Hybrid STFPID controller for BLDC motor drive. Section 5 validates the simulation results and the results of comparison with various controllers are presented. The hardware implementation and results are discussed in section 6 and section 7 presents the conclusion.

### 2 BRUSHLESS DC MOTOR DRIVE SYSTEM

![Fig. 1. Block diagram of BLDC motor drive system](image_url)

The block diagram of BLDC motor drive system with conventional PID controller is shown in Fig. 1. The PID controller regulates the speed by generating a reference current in accordance with the speed error. The hysteresis current controller regulates the stator winding current within the specified hysteresis band by appropriately generating the switching commands to the inverter devices in accordance with rotor position information.
3 SELF TUNING FUZZY LOGIC CONTROLLER

The self tuning fuzzy approaches have been proposed to enhance the adaptability of fuzzy controllers in presence of external disturbances. The techniques used to enhance the adaptability of fuzzy controllers are rule base modification, scaling factor tuning, inference mechanism improvement, and membership function redefinition and shifting. Amongst this, the scaling factor tuning method has significant impact on parameter variations and hence is explored in this work [21]. The block diagram of STFPID controller is shown in Fig. 2.

The STFPID controller includes control rule base for the gain updating factor ‘α’ called fuzzy tuner [22] in addition to a conventional fuzzy controller. The role of fuzzy tuner is to adjust the scaling gains such that the domain of the input and output variables may be varied so as to have faster settling time and fewer oscillations around the preset speed.

Fig. 2. Block diagram of self tuning FLC for BLDC motor drive system

In the Self tuning FL controller, the input speed error (e) and change of error (Δe) to the FL controller are divided into seven linguistic variables: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), and Positive Big (PB). The output gain from FL controller is divided into three linguistic variables: Positive (P), Negative (N), and Zero (Z). For the gain updating factor, the linguistic variables are ZE, PS, PMS, PM, PLM and PL which represent Zero, Positive Small, Positive Medium Small, Positive Medium, Positive Large Medium and Positive Large respectively. Here the rule base for controller gains and gain updating factor are presented in Table 1 and Table 2.

4 HYBRID SELF TUNING FUZZY PID CONTROLLER FOR BLDC DRIVE

This work envisages the application of hybrid STFPID controller for BLDC motor drive combining the advantages of PID controller at steady state and STFPID during transient state [23 – 25]. The flowchart representation of the proposed hybrid STFPID Controller is shown in Fig. 3.

Here, the hybrid controller consists of a simple logical comparator where a logical switching mechanism is employed which changes the control action from one controller to another controller based on the speed error value. The conventional PID controller is active when the speed error is less than 10 rpm whereas the hybrid STFPID controller is active when the error is greater than 10 rpm.

5 RESULTS AND DISCUSSION

To validate the performance of the controller, the BLDC motor drive is simulated in MATLAB/simulink environment. The following equations are used to model the BLDC motor [26].

The voltage equation is given as,
Fig. 3. Flowchart for Hybrid STFPID Control Algorithm

$$V_{dc} = 2 \left[ R_a i_a + (L - M) \frac{di_a}{dt} \right] + e_1 - e_2 = R_a i_a + L_a \frac{di_a}{dt} + e_1 - e_2$$  \hspace{1cm} (1)

where $L$ and $M$ are self-inductance and mutual inductance per phase respectively, $R_a$ is the stator winding, $e_1$ and $e_2$ are the back electromotive force (EMF) of current carrying phases windings, $i_a$ is the armature current.

$$R_a = 2R_s, \quad \Omega \quad and \quad L_a = 2 (L - M), \quad H$$  \hspace{1cm} (2)

The electromagnetic torque developed by the motor can be expressed as $T_e$,

$$T_e = T_L + J_M \frac{d\omega}{dt} + B_M \omega$$  \hspace{1cm} (3)

where $T_L$ is the load torque, $J_M$ is the inertia, and $B_M$ is the friction constant of the BLDC servomotor.

The output power developed by the motor is

$$P = T_e \omega$$  \hspace{1cm} (5)

$$E = e_a = e_b = e_c = K_b \omega$$  \hspace{1cm} (6)

where $K_b$ is back EMF constant, $E$ is back EMF per phase, and $\omega$ is the angular velocity in radians per second.

The parameters of the BLDC motor used in this work are tabulated in Table 3.

| Table 3. Motor parameters |
|---------------------------|
| Voltage                   | 310V          |
| Rated Current             | 4.52A         |
| Rated Speed               | 4600rpm       |
| Rated power               | 1 hp          |
| Stator phase resistance   | 3.07Ω         |
| Stator phase inductance   | 6.57mH        |
| Inertia                   | $1.8e^{-4}$ Kg m$^2$ |

The performance of the proposed Hybrid STFPID controller is compared with conventional controller under varying speed and load conditions. Steady state error, rise time, peak time, settling time and speed ripple are considered as performance measures for evaluating the performance of the controllers. To verify the robustness of the proposed controller different simulation studies under different conditions are performed and the results are articulated.

The speed response of the BLDC motor drive under no load, constant load of 0.5 Nm and constant speed of 1500 rpm with varying load along with convergence curve for different controllers is illustrated in Fig. 4, Fig. 5 and Fig. 6 respectively. Performance analysis of the controllers due to change in speed reference is summarized in Table 4, Table 5 and Table 6. The convergence plot depicted in the below figures indicate the fast tracking capability of the proposed controller. From the convergence curve and performance parameters, it is evident that the proposed controller performs better than fuzzy PID controller.

From the analysis, it is evident that the proposed controller is robust and has fast tracking capability with respect to parameter variations and has better steady state and dynamic characteristics which are highly desirable in industrial drive and automotive applications. The proposed controller augurs well for the above mentioned variable speed applications.
6 EXPERIMENTAL ANALYSIS

The experimental setup of the drive system is shown in Fig.7. The speed control algorithm is implemented using FPGA Spartan 3E board.

The experimental hall sensor output from the BLDC motor is shown in Fig. 8. The experimental voltage and current waveform for a speed of 1000 rpm is shown in Fig. 9 and Fig. 10 respectively. Fig. 11 shows the reference and actual speed response for the proposed controller at 1000 rpm. The hardware results indicate the suitability of the proposed controller for variable speed applications.

Table 4. Performance analysis of speed controllers in BLDC motor for change in speed at no load condition

| Controller   | Rise Time (sec) | Peak Time (sec) | Settling Time (sec) | Speed ripple | Steady State Error (rpm) |
|--------------|-----------------|-----------------|---------------------|--------------|--------------------------|
| Fuzzy PID    | 0.01            | 0.06            | 0.1                 | 0.1335       | 2.2628                   |
| Hybrid STFPID| 0.005           | 0.015           | 0.012               | 0.0003       | 1.3574                   |

Table 5. Performance analysis of speed controllers in BLDC motor for change in speed at constant load condition

| Controller   | Rise Time (sec) | Peak Time (sec) | Settling Time (sec) | Speed ripple | Steady State Error (rpm) |
|--------------|-----------------|-----------------|---------------------|--------------|--------------------------|
| Fuzzy PID    | 0.01            | 0.05            | 0.1                 | 0.1351       | 3.5075                   |
| Hybrid STFPID| 0.005           | 0.015           | 0.012               | 0.0006       | 3.1906                   |
Table 6. Performance Analysis of speed controllers in BLDC Motor for change in load with constant speed

| Controller   | Rise Time (sec) | Peak Time (sec) | Settling Time (sec) | Speed ripple | Steady State Error (rpm) |
|--------------|-----------------|-----------------|---------------------|--------------|-------------------------|
| Fuzzy PID    | 0.01            | 0.08            | 0.1                 | 0.13         | 0.8230                  |
| Hybrid STFPID| 0.0025          | 0.01            | 0.02                | 0.0003       | 0.5328                  |

7 CONCLUSION

The controller design for BLDC motor widely used in variable speed industrial and automotive applications need to account for non-linearity and parameter variations to ensure adaptability and robustness. It is in this outlook, hybrid STFPID controller has been proposed in this paper for speed control of BLDC Motor. The proposed hybrid STFPID controller combines the merits of PID controller and self tuning capability of fuzzy controller. To demonstrate its effectiveness, the performance of the proposed controller is compared with various controllers under varying speed and load conditions. The results indicate that the controller has less speed ripple, less steady state error and it is robust to load perturbation. The experimental results indicate the suitability of the proposed approach.

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Hybrid Self Tuned Fuzzy PID controller for speed control of Brushless DC Motor

Ramya A., Imthiaz A., Balaji M.

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A. Ramya received her B.E. degree in Electronics and Communication Engineering in 2008 and M.E. degree in Power Electronics and Drives in 2010 from Anna University Chennai, India. She taught as an Assistant Professor at the Electrical Engineering Department from 2010 to 2013. She is currently pursuing Ph.D in Electrical Engineering Department at Anna University Chennai, India since 2014. Her research areas include robust BLDC motor control, intelligent control and power electronics drives.
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Ramya A., Imthiaz A., Balaji M.

A. Imthiaz received his B.E degree in Electrical and Electronics Engineering from Anna University Chennai, India in 2014. He is currently working as a Design Engineer in Mango Ventures Llp, Ahmedabad, India. During his professional experience, he has designed, fabricated and tested SR and BLDC Motors. He has also designed control circuitry for SR and BLDC Motors. His research interest includes Design of Electric Motor, Electric Drives, and Power Electronics.

Dr. M. Balaji received his B.E degree in Electrical Engineering from Annamalai University, India, M.E degree in Power Electronics and Drives from Anna University Chennai, India and Ph.D in the area of Special Electrical Machines from Anna University Chennai, India. He is currently an Associate Professor in the Department of Electrical and Electronics Engineering in SSN College of Engineering, Chennai, India and has 12 years of teaching and research experience. His area of interest includes Design and Control aspects of Electrical Machines, Hybrid Electric Vehicles and Power Converters.

AUTHORS’ ADDRESSES
A. Ramya, M.E.
A. Imthiaz, B.E.
Dr. M. Balaji, Ph.D.
Department of Electrical and Electronics Engineering, SSN college of Engineering (Affiliated to Anna University), Kalavakkam, Chennai-603110, email: ramyaa@ssn.edu.in, aimthiazz@gmail.com, balajim@ssn.edu.in

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