Hybrid Fuzzy-PID Bidirectional Speed Controller for BLDC with Seamless Speed Reversal using Direct Commutation Switching Scheme

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***Abstract*—Brushless Direct Current (BLDC) motors have attracted a lot of attention due to their performance capabilities. The Proportional Integral (PID) controller remained popular due to its simplicity. However, PID's performance deteriorates during nonlinear loads conditions. Controllers have been developed to overcome the limitations of the PID controllers but focused on forwarding motor only. Furthermore, lack of literature regarding the bidirectional speed control of BLDC motor has been reported. In this paper, a Hybrid Fuzzy-PID speed controller for BLDC with seamless speed reversal using direct commutation switching scheme was proposed. The controller uses Fuzzy rule base and the switching scheme for bidirectional operations. MATLAB/Simulink was used to develop and test the controller. The controller was tested for several test cases and compared to a ZN-Tuned PID controller. The controller performed efficiently for all the test cases and has better results compared to the PID controller under same test cases.**

***Index Terms*—BLDC; Speed Controller; Fuzzy-PID; Hybrid; Bidirectional.**

I. INTRODUCTION

Brushless Direct Current Motor (BLDC) became a preferable motor in the industry and automation sectors due to low maintenance cost, higher efficiency and high-power density capabilities [1- 3]. An electronic commutation system is used to drive a BLDC motor, where the stator winding is energized in a sequence based on the position of the motor's rotor. This commutation system eliminates the commutator wear problem while reducing the motor losses and maintenance cost [4]. For a sensor-ed BLDC motor, the speed measurements and rotor positions are obtained using three or more hall sensors. Trapezoidal or rectangular voltage coupled with hall sensors drives the BLDC motor [5-8]. In order to ensure a BLDC motor operates at desired direction and speed, a closed loop speed controller is required.

Speed controller techniques such as Proportional (P), Proportional Integral (PI), Proportional Integral Derivative (PID) and fuzzy based techniques were developed over the years to adapt to application needs of BLDC motors [9-11]. Fuzzy based controllers are complex and expensive, this has allowed the PID controller to be preferred [12-14]. However, during nonlinear and uncertainties conditions that occur in the system the PID controller's performance become unstable [10,15-16].

Different types of intelligent control techniques based on fuzzy logic were developed to overcome PID controller's limitations. The author [15], developed Rapid Control for BLDC motor using Fuzzy while the author [17] developed a controller based on adaptive fuzzy logic scheme to control BLDC motor. Real-time level control using Fuzzy Gain Scheduling of PID controller was contrived by [18] and BLDC motor controller using online fuzzy monitored inference system with coactive neuro-fuzzy was contrived by [19]. In [20], Hybrid Self-Tuned Fuzzy PID was developed. The performance was compared to Self-Tuned Fuzzy PID. The developed controllers in [5, 16-21] were able to surpass the limitation of a PI controller, however, these controllers only focus on motor forwarding mode. The author [22], developed a BLDC motor dsPIC controller that able to operate in four quadrants and in [23] a bidirectional BLDC controller using digital control was developed. However, in both [22-23], the authors are unable to prove and provide an adequate data that the controller was able to operate in reverse motoring mode. Phase lag angle doubles during reversal motoring mode compared to forwarding mode due to position information error was proved in [24]. Therefore, the ideal position of the BLDC motor's rotor during reversal must be determined by the controller [5,22-23, 25].

A Hybrid Fuzzy-PID bidirectional speed controller for BLDC with seamless speed reversal using direct commutation switching scheme was proposed in this paper. By utilizing the Fuzzy PID's fuzzification rules and PID controller, the controller will control the speed based on required speed and directions. Matlab Simulink was used to design and test the system. The proposed controller and Ziegler–Nichols (ZN) Tuned PID Controller was tested with several test cases.

II. BLDC SPEED CONTROLLER

BLDC motor's modelling is similar to a three-phase synchronous motor; however, permanent magnets on the motor's rotor has made some of the dynamic characteristics of the BLDC motor different compared to the synchronous motor [7]. Figure 1 depicts commonly used BLDC Speed Controller. The BLDC motor's mathematical equation can be expressed as follows:

$$\begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ba} & L_b & M_{bc} \\ M_{ca} & M_{cb} & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

where the phase voltage of the motor is represented by Va, V_b and V_c while winding resistance of motor's stator is denoted as R_a, R_b and R_c. Motor's phase current is typified by i_a, i_b and i_c. The M_{ab}, M_{ac}, M_{ba}, M_{bc}, M_{ca} and M_{cb} represents mutual inductances between stator windings. Self-inductance of the motor is typified by L_a, L_b and L_c [21].

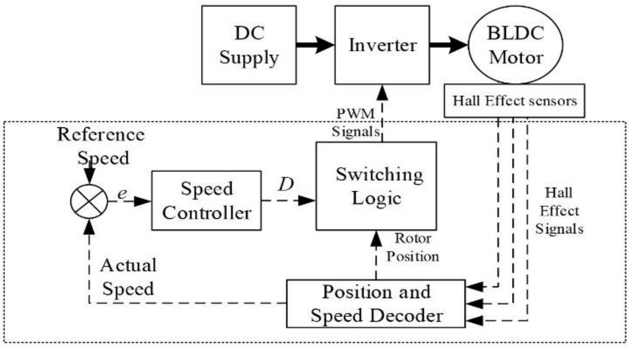

Figure 1: Speed Controller of BLDC Motor

The electro-mechanical torque is represented as

$$T_{em} = J\frac{d\omega_r}{dt} + \beta\omega_r + T_L \tag{2}$$

where J = moment inertia of rotor,
B = coefficient of friction,
ω_r = coefficient of angular velocity
T_L = mechanical load

In order to determine the 3-phase BLDC motor's electromagnetic torque the back-EMF, current and speed of the motor are required. The equation of electro-mechanical torque equation can be also typified as:

$$T_{em} = \frac{1}{\omega_m}(e_a i_a + e_b i_b + e_c i_c) \tag{3}$$

III. Proposed Controller

PID controller is a linear controller and could not perform efficiently during dynamic conditions. To address this problem, a hybrid controller was proposed. Figure 2 shows proposed controller. The controller consists of a fuzzy PID controller and a PID controller. The controller will determine the PWM generator's duty cycle of the based calculated error value *e(t)* by comparing the actual speed and the desired speed. To compensate for dynamic conditions, the system will select which controller to use based on current error value *e(t)*.

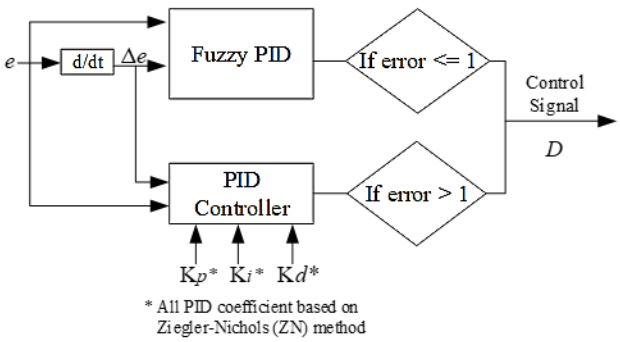

Figure 2: Proposed Controller

PID controller's mathematical equation can be represented as:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{\partial e(t)}{\partial t} \tag{4}$$

$$Kp = \Delta Kp + Kp' \tag{5}$$

$$Ki = \Delta Ki + Ki' \tag{6}$$

$$Kd = \Delta Kd + Kd' \tag{7}$$

where K_p proportional gain coefficient, K_i integration time coefficient and K_d derivative time coefficient. Previous sampling time's PID parameters are denoted by *Kp', Ki'* and *Kd'*. Δ*Kp*, Δ*Ki* and Δ*Kd* are output obtained from the fuzzy. Ziegler-Nichols (ZN) tuning method was used to obtain the PID's coefficients in this paper.

The developed controller uses similar equation as the PID controller to produce the duty cycle to control the PWM generator as shown in Figure 1. The internal structure of the fuzzy for the proposed controller has two inputs and three outputs. The rate of error Δ*e(k)* and current error *e(k)* acts as the inputs and Δ*Kp*, Δ*Ki* and Δ*Kd* were the outputs of the fuzzy. Figure 3 represents current error *e(k)* and rate of error Δ*e(k)*'s membership functions, where Positive Big (PB), Negative Small (NS), Positive Small (PS), Negative Big (NB), Positive Medium (PM), Zero (Z0), and Negative Medium (NM). Figure 4 represents the membership functions for Δ*Kp*, Δ*Ki* and Δ*Kd*. Rule table for Fuzzy PID's membership functions is shown in Table 1. This rule table was used to obtain the 49 set of membership function rules that used in the controller.

The fuzzy PID controller uses the Equation 5-7 and membership functions rules to decide the best value of Kp, Ki and Kd to suit the demand.

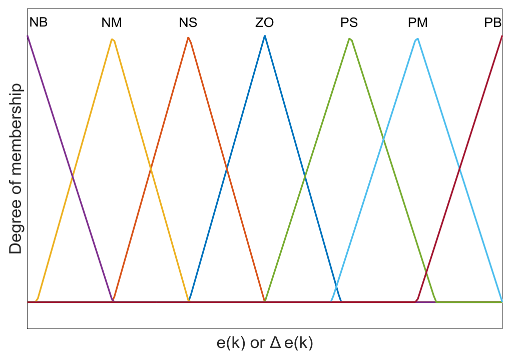

Figure 3: Membership function for e(k) and Δe(k)

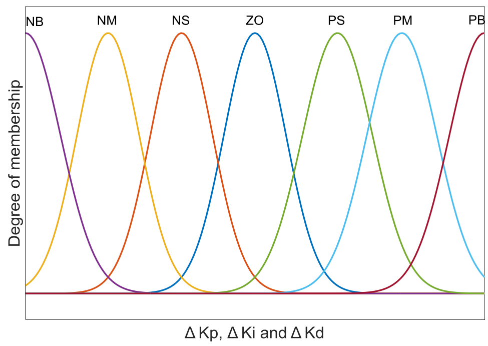

Figure 4: Membership function for ΔKp, ΔKi and ΔKd

Table 1
Fuzzy PID Kp, Ki and Kd Rules

Change of error $\Delta e(k)$	Error $e(k)$: NB	NM	NS	ZO	PS	PM	PB
	NB	NM	NB	PB	PB	PM	PB
NB	PS	PM	PB	NB	NB	NM	ZO
	ZE	PS	PS	NS	ZO	NS	ZO
	PB	NM	NM	PS	PM	NS	PS
NM	PS	PM	NS	NS	NM	PS	NS
	NS	ZO	NB	NM	ZO	NS	NB
	PB	PM	NS	PS	ZO	PS	NS
NS	NB	NM	PS	NS	ZO	NM	PS
	NM	NB	ZO	NS	PS	NB	ZO
	PS	PS	PS	ZO	PS	PS	NM
ZO	NS	NS	NS	ZO	NS	NS	PS
	NB	NM	NB	ZO	NB	NB	PS
	PS	NS	ZO	NS	PS	NS	NB
PS	NS	PS	ZO	PS	NS	PS	PS
	NB	NS	NS	NS	ZO	Z0	PS
	PM	NS	NS	NS	NM	PM	NB
PM	NS	ZO	PS	PM	PS	NM	PB
	ZO	NM	NS	NS	ZO	ZO	PS
	NS	NS	NS	NS	NB	PB	PB
PB	ZO	PS	PS	PS	PS	NS	NB
	PS	NS	ZO	ZO	ZO	NS	PS

Figure 5 depicts the Direct Commutation Switching scheme controller. This controller was developed using convoluted mathematical and commutation sequences of a BLDC motor. The BLDC speed controllers under test will be tested using this scheme.

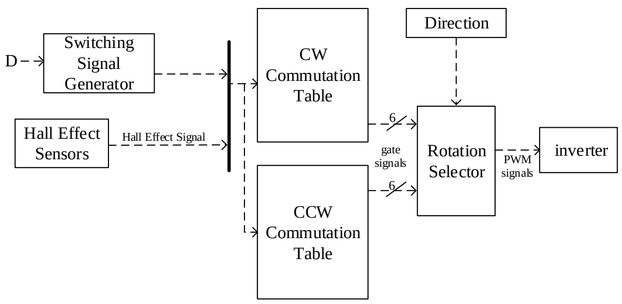

Figure 5: Direct commutation switching scheme controller

IV. Simulation Results and Discussion

The BLDC motor's specification that was used in the Matlab Simulink model is as shown in Table 2. Four test cases were used to test the proposed controller; (1) constant speed during no load condition, (2) constant speed during full load condition, (3) step - changing speed during full load conditions, (4) varying direction during full load conditions. The results of Settling time (Ts), overshoot (Mp), Steady State Error (e_{ss}), and Rise time (Tr) were compared to the ZN-Tuned PID Controller.

A. Constant Speed with No Load Condition

Speed reference of 1500rpm was set for both directions of counterclockwise (CCW) and clockwise (CW). No load was placed during this test case for both directions. The results are depicted in Figure 6 and Figure 7 and for CW direction and CCW direction. Table 3 and 4 show the BLDC motor's feedback for CW and CCW directions respectively. For both the ZN-Tuned PID and Hybrid Fuzzy PID controller, no overshoot was observed during both CW and CCW directions. Comparing both controllers it can be seen that, despite not having any overshoot the ZN-Tuned PID performed worse compared to the proposed controller. The proposed controller performed faster and has better rise time at 4.8 ms.

Table 2
BLDC Motor Specifications

Specifications	Value
Rated voltage (V)	500
Rated current (A)	2.23
Rated speed (rpm)	1500
Stator phase resistance R (Ω)	3
Stator phase inductance L (H)	0.001
Flux linkage (Vs)	0.175
Voltage constant (V/rpm)	0.1466
Torque constant (N m/A)	1.4
Moment of inertia (kg m2/rad)	0.0008
Friction factor (N m/(rad/s))	0.001
Pole pairs	4

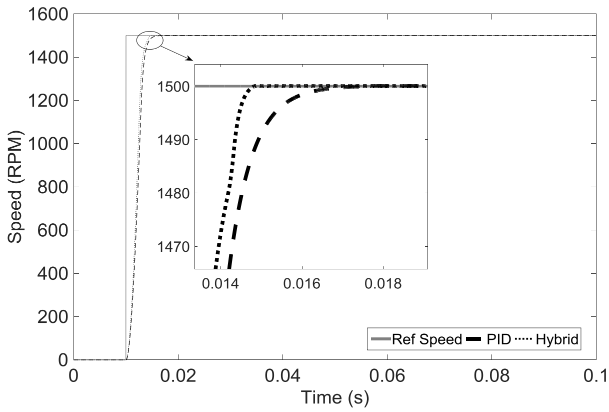

Figure 6: BLDC Motor Feedback during No Load for CW Direction

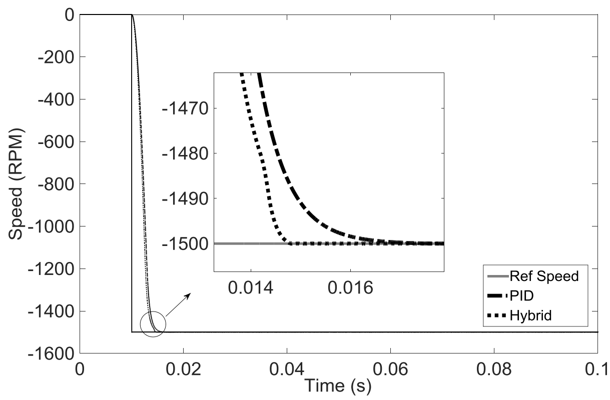

Figure 7: BLDC Motor Feedback during No Load for CCW Direction

Table 3
BLDC Motor Feedback for CW during No Load

Techniques	T_r (ms)	M_p (%)	T_s (ms)	e_{ss} (%)
ZN-Tuned PID	7.70	-	7.70	0.00123
Hybrid Fuzzy PID	4.80	-	4.80	0.00059

Table 4
BLDC Motor Feedback for CCW during No Load

Techniques	T_r (ms)	M_p (%)	T_s (ms)	e_{ss} (%)
ZN-Tuned PID	7.70	-	7.70	0.00123
Hybrid Fuzzy PID	4.80	-	4.80	0.00059

B. *Constant Speed During Full Load Condition*

The BLDC motor feedback for a full load of 3 Nm during CW and CCW directions were represented by Figure 8 and Figure 9 subsequently. The data was tabulated in Table 5 and 6 respectively. For both directions, the Hybrid Fuzzy PID has the fastest rise time of 5.2 ms and smallest *ess* of 0.0073 %.

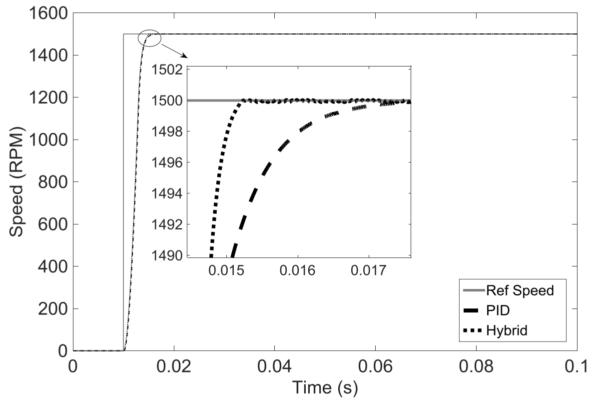

Figure 8: BLDC Motor Feedback during CW Direction for Full Load

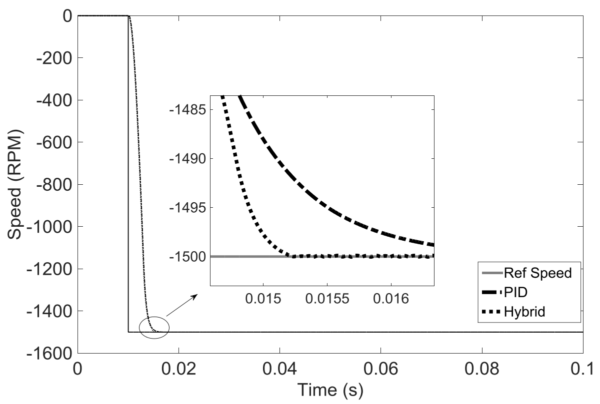

Figure 9: BLDC Motor Feedback during CCW Direction for Full Load

Table 5
BLDC Motor Feedback for CW during Full Load

Techniques	T_r (ms)	M_p (%)	T_s (ms)	e_{ss} (%)
ZN-Tuned PID	8.50	-	8.50	0.01041
Hybrid Fuzzy PID	5.20	-	5.30	0.00730

Table 6
BLDC Motor Feedback for CCW during Full Load

Techniques	T_r (ms)	M_p (%)	T_s (ms)	e_{ss} (%)
ZN-Tuned PID	8.50	-	8.50	0.01040
Hybrid Fuzzy PID	5.20	-	5.30	0.00730

C. *Step-changing Speed During Full Load Conditions*

Figure 10 shows the BLCD motor's full load of 3 Nm step-changing speed response at t = 0.05 s and the motor respond was tabulated in Table 7. No overshoot was observed for both controllers as the speed increased from 1500 rpm to 2000 rpm. With both rise time and settling time during the speed increase at 5 ms shows the Hybrid Fuzzy PID has superior performance than the PID controller. Steady state error (e_{ss}) has increased for both controllers, however, the values were under accepted value during the speed change for both controllers.

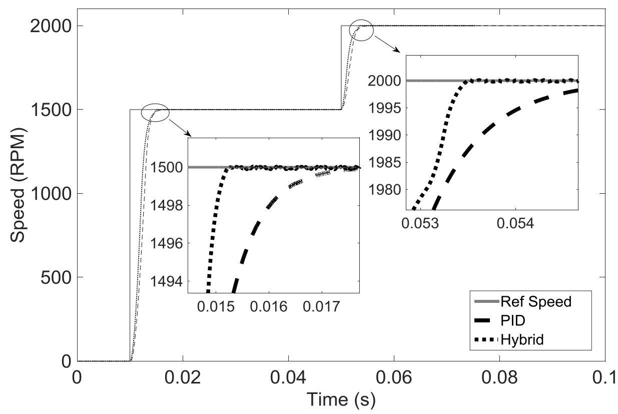

Figure 10: BLDC motor Feedback during CW Direction for Full Load

Table 7
BLDC Motor Feedback for the Step-Changing Speed

Techniques	Step change T_r (ms)	Step change T_s (ms)	Before Speed Change e_{ss} (%)	After Speed Change e_{ss} (%)
ZN-Tuned PID	6.70	6.90	0.0104	0.0135
Hybrid Fuzzy PID	5.00	5.00	0.0073	0.0110

D. *Varying Direction During Full Load Conditions*

The BLDC motor feedback for varying direction during full load conditions represented by Figure 11 for both controllers under test. Both controllers were able to accommodate the speed and direction changes. The Hybrid PID controller has the shortest settling time of 6.9 ms. However, e_{ss} of Hybrid Fuzzy PID increases as the direction changes but the ZN-Tuned PID's e_{ss} reduces as the direction changes.

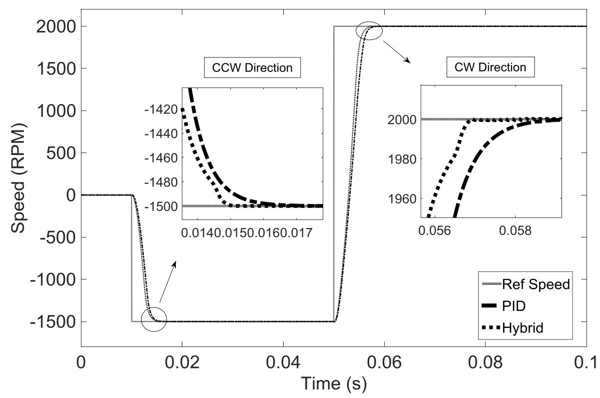

Figure 11: BLDC Motor Feedback during Full Load for both directions

Table 8
BLDC Motor Feedback in Varying Direction for Full Load

Techniques	CW T_r (ms)	CW T_s (ms)	CCW e_{ss} (%)	CW e_{ss} (%)
ZN-Tuned PID	9.7	9.7	0.0104	0.0054
Hybrid Fuzzy PID	6.9	6.9	0.0111	0.0112

V. Conclusion

In this study, a Hybrid Fuzzy-PID Bidirectional Speed Controller for BLDC with Seamless Speed Reversal using Direct Commutation Switching Scheme was proposed. For all test cases, the proposed controller was able to achieve better results than the PID controller. The Hybrid controller's steady state error was slightly higher compared to its counterpart during full load direction change. Despite having a slightly higher steady-state error, the error was within acceptable region. Hence a BLDC motor can be driven bidirectionally using this controller.

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