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Artificial Intelligent Based Controllers and IMC-PID Controller for Brushless DC Motor Speed Control in Hybrid Electric Vehicle

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Abstract— *The Brushless DC (BLDC) motors are more effective and potentially recognized in Hybrid Electric Vehicle (HEV) applications due to the several advantages entailed such as simple control, high speed operation, no sparking, rugged construction, less maintenance, high reliability, low noise, high powered density and high efficiency unlike other kind of motors that are difficult to used because of their fixed speed characteristics. The presence of mechanical commutation, high energy losses and non-linearity of the BLDC motor parameters makes it difficult to achieve a satisfactory speed control performance using convectional controllers of Proportional Integral (PI), Proportional Derivative (PD) and Proportional Integral Derivatives (PID) controllers. Therefore, this work proposed an Internal Model Controller (IMC) based PID controller for controlling the BLDC motor speed control. IMC is employed to enhance the performance of PID controller for a better minimization of the steady state speed error, rise time, settling time and overshoot percentage. Bode plot; Nyquist plot and Root Locus plot were used to determine the motor stability and its frequency responses. Hence, the significant factors derived from BLDC speed control using IMC-PID controller is to gives a satisfactory speed control performance, provide smooth throttle movement, zero steady state speed error and maintained a selected vehicle speed under different operating condition.*

Keywords— *Brushless DC motor: IMC-PID controller: Speed control.*

I. INTRODUCTION

Brushless DC (BLDC) motor drive is a power actuator which transforms electrical energy into mechanical energy. It is widely used in many industrial applications such as electric cranes, electric vehicle and robotic manipulators due to its intrinsic robustness, wide speed range with full torque control and high torque-to-weight ratio [1, 2]. BLDC motor is an electronically controlled commutation (no brushes), longer operating life, rugged construction, high efficiency and noiseless operation over Switched Reluctance (SR) Motor, Induction Motor (IM) and Permanent Magnet (PM) Motor [2]. Selecting the most appropriate electric propulsion system for HEV is a challenging task since the motor speed is directly proportional to the armature voltage and inversely proportional to the magnetic flux produce by the poles magnets [3]. Hybrid Electric Vehicles (HEVs) utilizes its propulsion gain through Internal Combustion Engine (ICE) and electric motor [4]. In low speed condition, HEV propel using electric motor while in high speed condition, the vehicle uses both ICE and electric motor to propel under load condition. BLDC motor plays a significant role in HEVs, due to the ability to supply energy to increase the efficiency and regenerate the braking system for optimizing the power usage [5]. The advantages of BLDC motor in HEV is the simple control associated with the vehicle such as high starting torque, wide speed range, high performance operation, accurate rapid braking, high-speed cruising, low exhaust emission, low acoustic noise, high-efficiency generation over a wide torque and speed range [6, 7]. The development of the rugged solid-state power semiconductors, non-linearity, high energy losses of the electromagnetic property and the winding current of BLDC motor operates in saturation condition makes the performances extremely difficult to achieve a steady state satisfactory control using convectional PID controller without a proper incorporation of optimization tuning technique. Several authors have made laudable efforts to control BLDC motor speed on load toque variation using PID controller, however due to the difficulty on proper optimization tuning [8]. Authors in [9] reported that the performance of IMC outsmart that of PID controller in terms of speed tracking ability, steady state response and rejection of load disturbance response. PID controller has optimum dynamics control as well as impressive properties due to its simplicity, clear functionality, reliability and applicability to linear system, reduce steady state error, fast response, easy to implement, no oscillations, higher stability and robust performance [10, 11]. The Proportional (P) is responsible for the desired set point and adjusts the output controller [11], Integral (I) is used to remove the steady state error and improve the steady state response [12] and Derivative (D) is used to improve the transient response of the system [13].

In similar vein, author in [14] presented a paper for PI, PD and fuzzy logic controller BLDC motor speed control and equations to calculate the error in related to the motor parameters on load variation. The author applied fuzzy control theory to the speed regulating system based on the mathematical model. As surveyed, the latest research lacks

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variety in speed controlling techniques due to increase in overshoot [15]. This paper present the simplicity, adaptively, flexibility and robust performance of IMC with the mathematical precision of PID controller for BLDC motor speed control to overcome the non-linearity problem, torque ripple, minimize overshoot percentage and speed control associated with BLDC motor stability, frequency response and changing in reference speed.

II. Proposed System

The reference speed has been set to 1400-3000 rpm at 415Vac, 50Hz using tachometer and the BLDC motor model was powered using a three phase power inverter is shown in Figure 1. The desired motor speed was measured and sent into the comparator, the rotational speed was sense through the speed sensor and sent into the comparator to determine the speed error, its derivative serves as an input into internal model controller to produce three outputs of the PID gains of K_P, K_I, K_D. The internal model controller auto-tune the PID in order to regulate the actual speed and have the pre-set value as the output. The multi mode operation of BLDC motor in HEV shown in Figure 2 encompasses the features of both the parallel and the series HEV architectures.

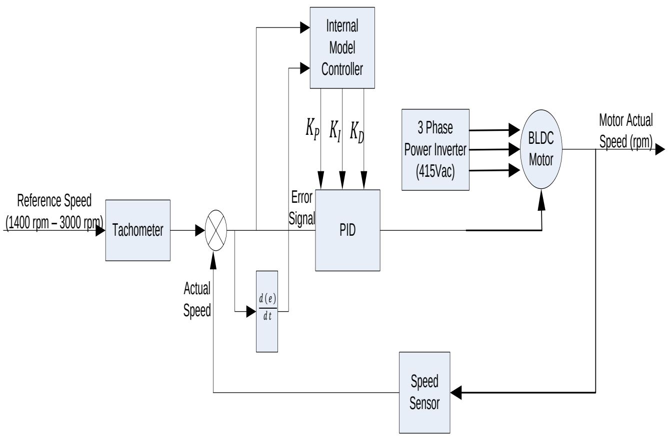

Fig. 1. Model for BLDC Speed Control Using IMC-PID Controller

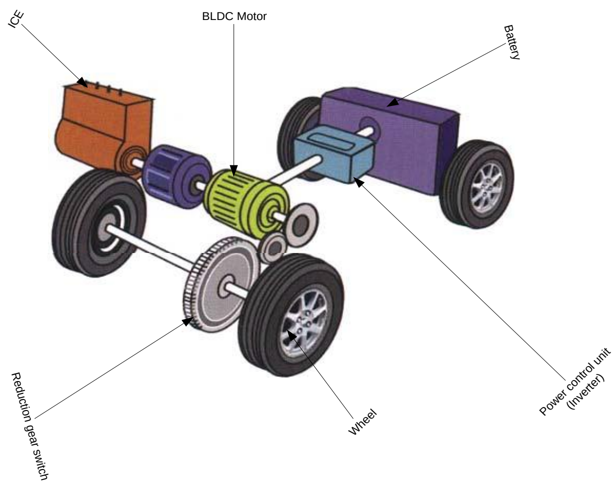

Fig. 2. Model of Hybrid Electric Vehicle

The Series mode is achieved by using the planetary gear to decouple the engine speed from the wheel speed. The decoupling of the engine from the wheels is done by adjusting the speed of the motor. Thus, it allowed the engine to operate at its most efficient operating points at all times. Additionally, the parallel mode responsible for locking the stator and rotor of the motor together de-energizes it. When stator and rotor of the motor are locked in place, the planetary gear unit becomes a simple gearbox with a single fixed gear ratio, thus allowing the vehicle to operate in parallel mode.

III. Mathematical Modeling Equations

The linear analysis of the electromechanical torque mathematical model of BLDC motor shown in Figure 3 described R_a as the armature resistance of the rotating coil in the motor, L_a as the inductance of the coil and E_b as the back EMF voltage. The coil on the rotor rotate in the magnetic field when the angular velocity of the load increase the voltage generated by back EMF increase to give BLDC motor a top speed.

The back EMF E_b is proportional to the angular velocity ω_m in rad/sec

$$E_b(t) = K_b\,\omega_m(t) \qquad (1)$$

The motor torque T_m is proportional to the angular velocity ω_m by the moment of inertia of the load I_l

$$T_m(t) = I_l\,\omega_m(t) \qquad (2)$$

The motor torque T_m is proportional to the armature current i_a by a torque constant K_t

$$T_m(t) = K_t i_a(t) \qquad (3)$$

The mechanical operation of BLDC motor

$$T_m(t) = \frac{d\omega_m}{dt} + B_m\omega_m(t) \qquad (4)$$

The voltage across the armature resistance, inductance and back EMF is given as:

$$E_a(t) = R_a i_a(t) + L_a\frac{di_a}{dt} + E_b(t) \qquad (5)$$

At no load, "(2)" is equal to "(3)"

$$I_l\,\omega_m(t) = K_t i_a(t) \qquad (6)$$

Take the differential equation of the angular velocity of the motor

$$\frac{d\omega_m(t)}{dt} = \frac{K_t i_a(t)}{I_l} \qquad (7)$$

Substitute "(1)" into "(5)" and take the Laplace transform of "(5)" and "(7)"

$$E_a(t) = R_a i_a(t) + L_a\frac{di_a}{dt} + K_b\,\omega_m(t) \qquad (8)$$

$$E_a(s) = R_a i_a(s) + sL_a i_a(s) + K_b\,\omega_m(s) \qquad (9)$$

$$s\omega_m(s) = \frac{K_t i_a(s)}{I_l} \qquad (10)$$

The motor output is proportional to the rotational speed and armature voltage

$$P_{(s)} = \frac{\omega_m(s)}{E_a(s)} \qquad (11)$$

$$i_a(s) = \frac{s\omega_m(s)I_l}{K_t} \qquad (12)$$

Substitute equation (1) into equation (5) to get the BLDC motor power output

$$E_a(s) = \left[R_a\frac{s\omega_m(s)I_l}{K_t} + sL_a\frac{s\omega_m(s)I_l}{K_t} + K_b\,\omega_m(s)\right] \qquad (13)$$

$$E_a(s) = \left[s^2L_a\frac{\omega_m(s)I_l}{K_t} + sR_a\frac{\omega_m(s)I_l}{K_t} + K_b\,\omega_m(s)\right] \qquad (14)$$

$$\frac{\omega_m(s)}{E_{a(s)}} = \frac{K_t}{[s^2 J_l + sRJ_l + K_b]} \quad (15)$$

$$P_{(s)} = \frac{\omega_m(s)}{E_{a(s)}} = \frac{K_t}{[s^2 J_l + sRJ_l + K_b]} \quad (16)$$

A. *Closed Loop Mathematical Modeling Equation*

The closed loop for BLDC motor based Proportional Integral Derivative (PID) controller is shown in Figure 3. Equation (17) shown the transfer function of the PID controller

$$G_p(s) = \frac{U(s)}{E(s)} = K_p + K_d s + \frac{K_i}{s} \quad (17)$$

$$G_{(s)} = P_c(s) + G_p(s) \quad (18)$$

$$G_{(s)} = \frac{K_t[K_p s + K_d s^2 + K_i]}{s[s^2 J_l + sRJ_l + K_b]} \quad (19)$$

Where: K_T is torque constant of Nm/A, T_m is motor torque of Nm, I_l is moment of inertia of the load in $Kg.m^2$, $E_a(t)$ is input voltage in v, ω_m is motor speed of $\frac{rad}{s}$, R_a is the armature resistance in Ω, J_L is moment of inertia in $Kg.m^2$, B_m is the coefficient of friction of $\frac{Nm}{\frac{rad}{s}}$, K_b is motor back EMF constant of $\frac{v}{rad}/sec$, L_a is armature inductance in H, I_a armature current in A, K_P is proportional gain, P_{BLDC} is motor output power in KW, E_b is motor back EMF voltage $\frac{v}{\frac{rad}{sec}}$, $G_{(s)}$ is the overall transfer function of a PID controller, K_D is Derivative gain, K_I is Integral gain and $G_p(s)$ is Forward path transfer function of PID controller

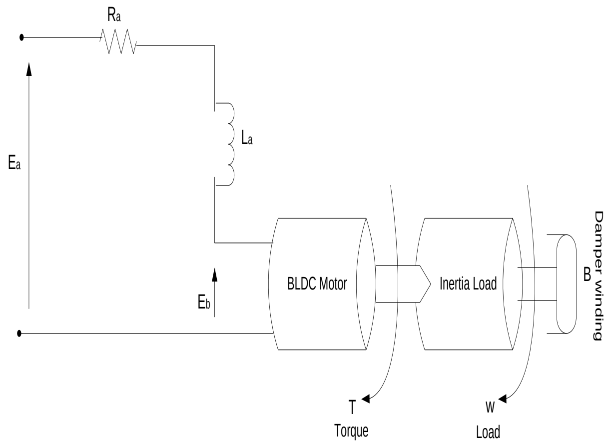

Fig. 3. Model of a BLDC Motor

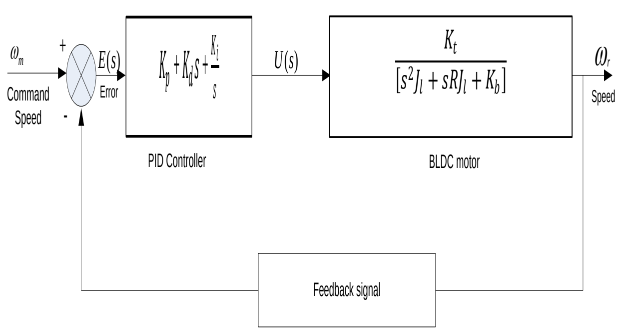

Fig. 4. BLDC-PID Closed Loop System

B. *Internal Model Controller*

IMC controller allows good set-point tracking but sulky disturbance responses especially for the process with a small time delay and time constant ratio. The controller works for different values of filter tuning parameter in order to achieve the desired responses. It helps to determine the model error by subtracting the model output from the process output as stated in "(20)". The modified set point corrects the error, thus an error free output is obtained as the measured process output. The IMC gives an off set free response at the steady state on the process model "G_p*(s)". The asterisk symbol '*' represent that the signal is associated with the model; r is the desired set point, r' is the modified set point and d is the disturbance.

$$r' = r - d^* \quad (20)$$

$$G_{P*}(s) = \frac{K_{P*}}{[T_{P*}(s)+1]} \quad (21)$$

The simulation parameters used in this work and the MATLAB/Simulink model of the BLDC motor is as shown in Table I and Figure 9 respectively. The simulation results of different control algorithms implemented in this work is presented and discussed in this section IV.

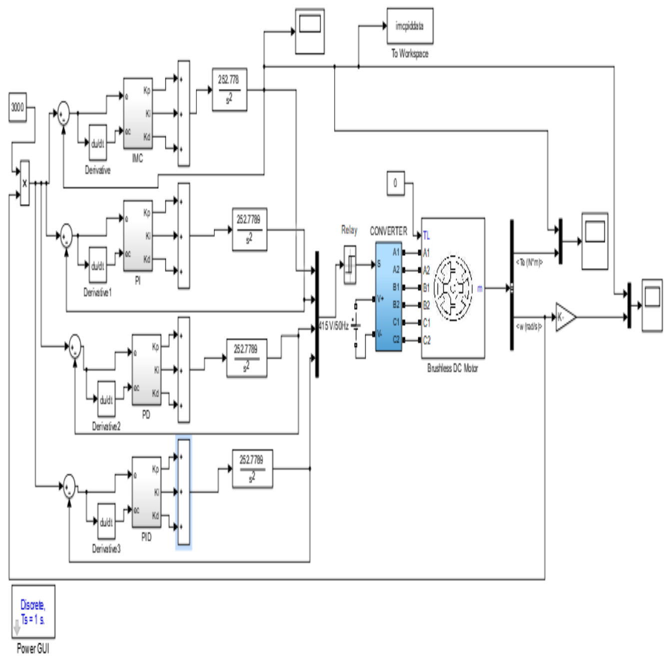

Fig. 5. Simulink of BLDC Motor Speed Control

TABLE I.

S. No.	Simulation Parameters	
	Motor Parameters	Values
1	P_{BLDC}	40KW
2	Reference speed:	1400-3000rpm
3	Armature inductance:	0.000432
4	Torque constant:	0.0125
5	Armature current:	1.86
6	Armature resistance:	6.8
7	Motor Back EMF constant:	0.525
8	Coefficient of friction:	0.00207
9	Moment inertia force:	0.0085
10	Input voltage:	400
11	Motor Back EMF voltage:	0.0525

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IV. RESULTS AND DISCUSSIONS

The stability and its frequency responses of the BLDC motor speed was achieved using Bode plot, Nyquist plot and Root locus plot is shown in Figure 6-8 respectively. Bode plot is useful for finding the system stability, gain and phase margin. In the low frequency responses the magnitude was above 20 Log (1/p) and beyond p it decreases at the rate of 20decibel per decade. The phase plot shows that the initial phases close to zero and decrease at the rate of 45degree per decade until it reaches – 90degree as the frequency goes beyond 10p. Hence, the system has adequate stability margins. Nyquist plot measured the system stability, phase and gain stability margin needed at the frequency domain. In the plot all the poles lies in the LHS of the S-plane and for the closed loop system the gain K = 10, the poles lie in the LHS of the plane. Hence, the result indicates the system is stable. The root locus plot of the BLDC motor, having all the poles G(s) located in the open left half of the S-plane was very desirable, P = 0 represent open loop of the stable system. Thus, Z = P – N= 0. Hence, the system was stable since there is no close loop pole in the left hand plane.

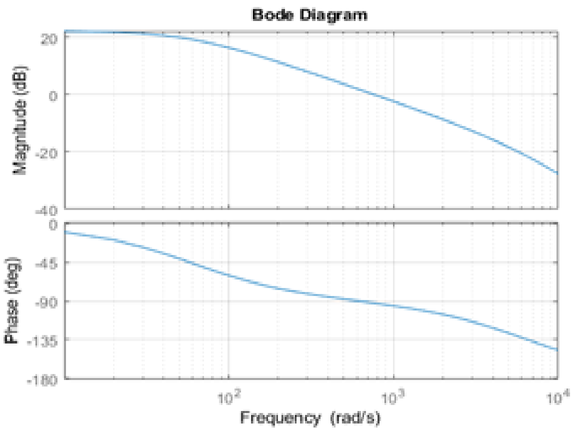

Fig. 6. Bode plot for BLDC Motor

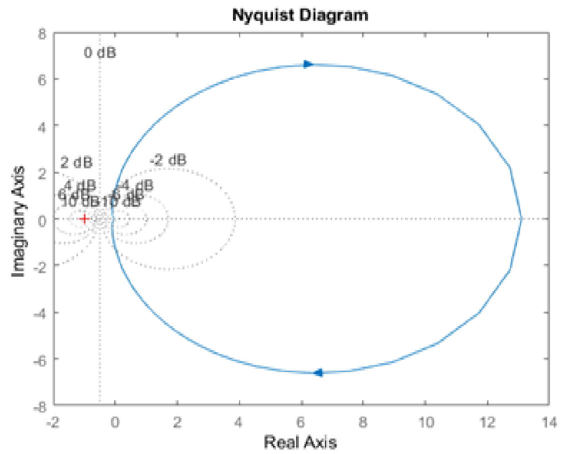

Fig. 7. Nyquist plot for BLDC Motor

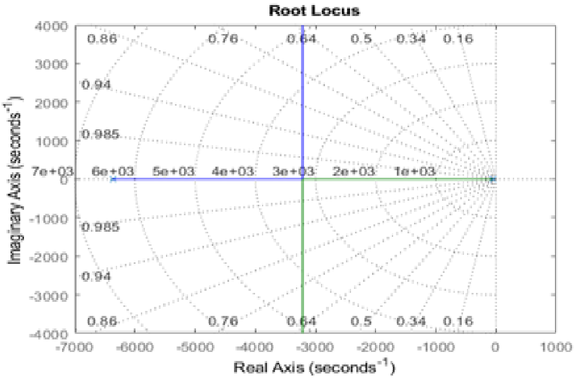

Fig. 8. Root Locus plot for BLDC Motor

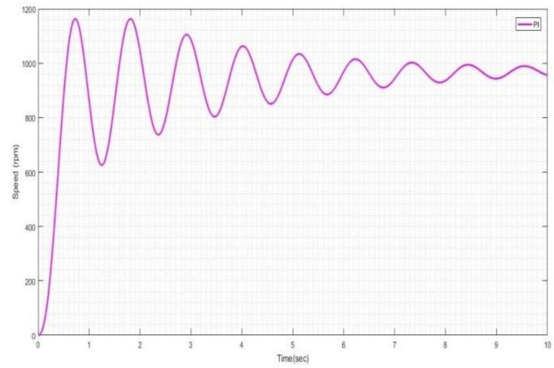

Fig. 9. PI Controller for BLDC Motor Speed at 1400rpm

The performance of the BLDC motor speed control obtained with Proportional Integral (PI), Proportional Derivative (PD), Proportional Integral Derivative (PID) and Internal Model Control Proportional Integral Derivative (IMC-PID) controller at a reference speed of 1400rpm is as shown in Figure 9-12 respectively. Figure 9 shows the performance of proportional integral controller at a speed of 1400 rpm. The rise time for the percentage overshoot of 46.925% was 0.359sec while the settling time was 9.786sec of the steady state error.

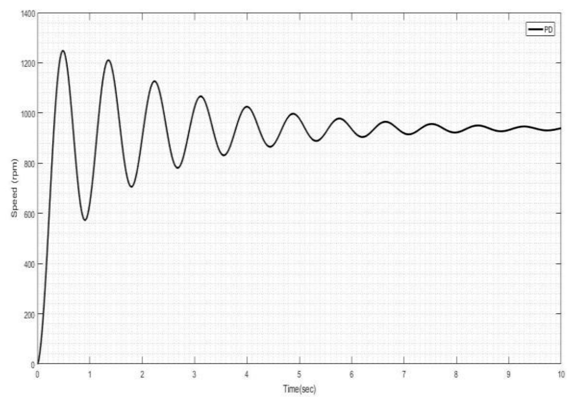

Fig. 10. PI Controller for BLDC Motor Speed at 1400rpm

Figure 10 shows the performance of proportional derivative controller at a speed of 1400 rpm. The rise time for

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the percentage overshoot of 32.920% was 0.296sec while the settling time was 8.165sec of the steady state error.

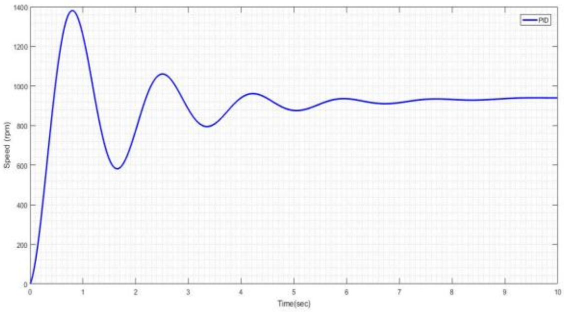

Fig. 11. PID Controller for BLDC Motor Speed at 1400rpm

Figure 11 shows the performance of proportional integral derivative controller at a speed of 1400 rpm. The rise time for the percentage overshoot of 20.689% was 0.198sec while the settling time was 7.139sec of the steady state error.

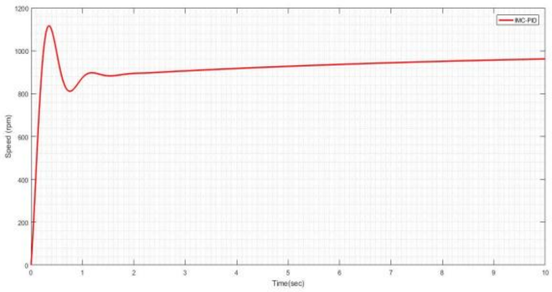

Fig. 12. IMC-PID Controller for BLDC Motor Speed at 1400rpm

Figure 12 depicted the performance of internal model control tuned proportional integral derivative at a speed of 1400 rpm. The rise time for the percentage overshoot of 15.108% was 0.102sec while the settling time was 6.672sec of the steady state error.

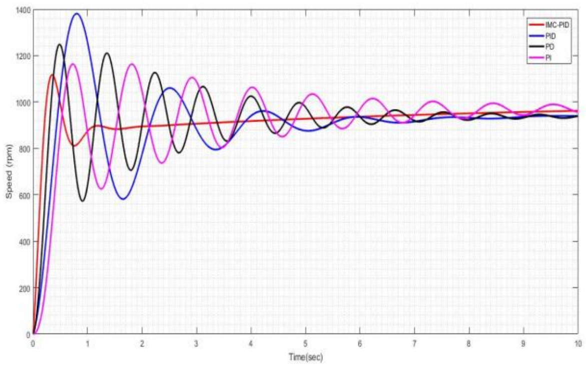

Fig. 13. Comparison of PI, PD, PID and IMC-PID of BLDC Motor Speed at 1400rpm

Figure 13 shows the comparison performances of PI, PD, PID and IMC-PID controller in terms of rise time, settling time and overshoot percentage at the speed of 1400 rpm. The summary results of the controllers as validated that IMC-PID controller has the least in rise time of 0.102sec, settling time of 6.672sec and overshoots percentages of 15.108% as shown in Table II.

TABLE II.

S. No.	Comparison of PI, PD, PID and IMC-PID for BLDC Motor Speed at 1400rpm			
	Controllers	Rise Time (sec)	Settling Time (sec)	Overshoot (%)
1	PI	0.359	9.786	46.925
2	PD	0.296	8.165	32.920
3	PID	0.198	7.139	20.689
4	IMC-PID	0.102	6.672	15.108

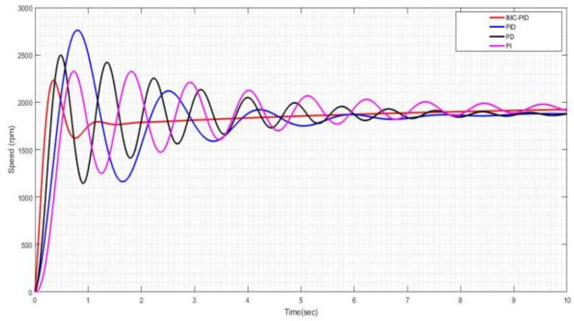

Fig. 14. Comparison of PI, PD, PID and IMC-PID of BLDC Motor Speed at 3000rpm

Figure 14 depicted the comparison performances of PI, PD, PID and IMC-PID controller in terms of rise time, settling time and overshoot percentage with increased in speed of 3000rpm obtained. The summary results of the controllers as indicated that IMC-PID controller has the least in rise time of 0.156sec, settling time of 6.938sec and overshoots percentages of 28.303% as shown in Table III.

TABLE III.

S. No.	Comparison of PI, PD, PID and IMC-PID for BLDC Motor Speed at 3000rpm			
	Controllers	Rise Time (sec)	Settling Time (sec)	Overshoot (%)
1	PI	0.468	11.870	52.860
2	PD	0.381	9.921	48.702
3	PID	0.293	7.860	35.232
4	IMC-PID	0.156	6.938	28.303

V. CONCLUSION

The optimization tuning technique of IMC is incorporated to PID controller for controlling the speed of the BLDC motor as used in automotive industries to give a satisfactory speed control performance in order to provide smooth throttle movement, zero steady state speed error and maintain a selected vehicle speed on load variation. The motor stability and its frequency responses were achieved with Bode plot, Nyquist plot and Root locus plot. The performances of PI, PD, PID and IMC-PID in terms of rise time, settling time and overshoot percentage were investigated in this paper. The simulation result showed that IMC-PID controller demonstrated a superior performance over other controllers investigated based on the performance metrics used. The time taken for IMC-PID controller to reach the steady state value is lesser and the percentage overshoot is minimized. Hence,

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further studies can consider utilization of Fuzzy based PID which involves the optimization of Fuzzy parameters set, membership function and proper choice of rule.

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