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Abstract: This Paper presents a framework to carry out a simulation for closed loop speed control of BLDC motor with PID and Modified PID controller. The novelty of this paper lies in the design of modified PID controller to track the reference trajectory with and without load in addition to minimizing the initial overshoot. The simulation includes all realistic values and components of the motor. The three phase inverter and its control algorithm is modeled and simulated using MATLAB Simulink. The PID and Modified PID controller track the reference speed with and without load disturbances in closed loop control but the demerit of conventional PID can be observed in its steep overshoot in the closed loop transient response. The speed, torque, dc-link current and back-emf waveforms are analyzed for various load torque conditions through MATLAB Simulink.

Keywords: BLDC Motor, PID, Modified PID, VSI, Rise/Settling time, Minimum overshoot, MATLAB.

1. Introduction

Recently, the small and medium size motor industries are developing rapidly because of its simple and small structure. The BLDC motor has the advantages of high efficiency, long life time, good speed torque characteristics and high toque to weight ratio compared to DC, Induction and Switched Reluctance motor. It is used in the field of electric drives, aerospace engineering, robotics and household's equipment etc. The paper [1][7][8][12] discusses about the design of conventional and fractional order PID controller for BLDC Motor for closed loop speed control and their performances are compared. Design of Adaptive Neuro-Fuzzy PID controller for AVR system using optimization technique based on SNR-PSO was reported in the literature [2] and the results displayed that the efficiency of SNR-PSO based ANFIS controller is superior than robust PID controller. In the Paper [3], the performance of Induction Motor drive for direct torque and flux control using fuzzy logic and sliding mode speed control was presented and the robustness analysis in presence of parameter uncertainty and load disturbances was carried out. The authors in the paper [4] proposed a novel Proportional Integrator Current Chopping Control (PICCC) method for torque-ripple minimization of Switched Reluctance Generator in presence of load disturbances. Application of Fuzzy logic technique in speed control of doubly fed induction motor using fuzzy PI controller in presence of load torque disturbances is reported in the paper [5]. Application of evolutionary algorithm (Genetic algorithm, Particle Swarm optimization) in designing an optimal controller for motor drives are explored in the literature [6][8][12]. The reference [11] provides an overview of the design of PID and Fuzzy PID controller for BLDC motor and their closed loop responses are compared. The paper [10][12] introduces a concept on the Mathematical modeling and Simulation of the BLDC Motor. The authors in the paper [9] proposed a method to control speed of three phase Induction Motor using Fuzzy PID controller and compared their result with conventional PID in MATLAB/Simulink.

In this paper, the authors have proposed a novel controller design method based on the concept of dominant pole placement for closed loop speed control of BLDC motor. The transient performance obtained from the Modified PID controller is compared

with the responses obtained from conventional PID controller and results demonstrate the superiority of Modified PID controller.

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2. Three Phase Inverter Model with 120 degree conduction mode

Simulating an inverter of a BLDC motor in Simulink uses phase currents, back-EMF, rotor position and dc-source voltage as inputs. Table 1 shows the switching sequences depending upon different rotor position and three phase voltages of the motor.

Sequence	Rot H _a	or posi H _b	tion H _c	Switching (ON)	А	Phase Current B	С
1	1	0	1	Sw6 , Sw1	E _{dc} +	E _{dc} -	OFF
2	1	0	0	Sw1 , Sw2	$E_{dc}+$	OFF	E _{dc} -
3	1	1	0	Sw2 , Sw3	OFF	$E_{dc}+$	E _{dc} -
4	0	1	0	Sw3 , Sw4	E _{dc} -	E _{dc} +	OFF
5	0	1	1	Sw4, Sw5	E _{dc} -	OFF	E _{dc} +
6	0	0	1	Sw5 , Sw6	OFF	E _{dc} -	$E_{dc}+$

Table	1.	Switching	Sequences
1 abic	т.	Switching	bequences

<u>MODE – 1</u> If $H_a = 1$, $H_b = 0$, $H_c = 1$ then, Sw1 and Sw6 are ON (previously Sw5 and Sw6 were ON)



Figure 1. Current path through the three phase inverter for the Mode 1, where the path represented by bold lines with arrows represents the current through the active phase, and the dotted path represent the commutating current from the previous switching sequence.

When $i_C \neq 0$, the three phase-to-phase voltages can easily be derived from Figure 1.

$$V_{AB} = +E_{dc} \qquad (1)$$
$$V_{BC} = 0 \qquad (2)$$

-----(2) $V_{CA} = -E_{dc}$ ------(3) [:: $V_{CA} = -(V_{AB} + V_{BC})$] where, V_{BC} represents the voltage over the reversed biased diode, D2.

A simplified circuit is shown in Figure 2 for the Mode 1



Figure 2. Circuit diagram for Mode 1.

KVL are applied around each mesh in Figure 2 to obtain the three phase to phase voltage, i.e,

$$E_{dc} - Ri_{A} - L\frac{di_{A}}{dt} - e_{A} + e_{B} - L\frac{d(i_{A} + i_{C})}{dt} - R(i_{A} + i_{C}) = 0 - \dots - (4)$$

-V_{BC} - Ri_C - L $\frac{di_{C}}{dt} - e_{C} + e_{B} - L\frac{d(i_{A} + i_{C})}{dt} - R(i_{A} + i_{C}) = 0 - \dots - (5)$

When $i_C = 0$ and put $i_A = i$ in equation (4) and (5), we get

$$E_{dc} - 2Ri - e_A - 2L\frac{di}{dt} + e_B = 0$$

$$-V_{BC} - Ri - L\frac{di}{dt} - e_C + e_B = 0$$

$$(6)$$

Equation (6) and (7) gives

$$-V_{BC} - e_{C} + e_{B} + \frac{1}{2} \left[-E_{dc} + e_{A} - e_{B} \right] = 0 - \dots - (8)$$

Hence, $V_{BC} = \frac{1}{2} \left[-E_{dc} + e_{A} + e_{B} - 2e_{C} \right] - \dots - (9)$

So, three phase to phase voltages will be

$$V_{AB} = +E_{dc} \qquad (10)$$

$$V_{BC} = \frac{1}{2} \Big[-E_{dc} + e_A + e_B - 2e_C \Big] \qquad (11)$$

$$V_{CA} = \frac{1}{2} \Big[-E_{dc} - e_A - e_B + 2e_C \Big] \qquad (12) \quad [\because V_{CA} = -(V_{AB} + V_{BC})]$$

The same derivation is applied for the rest of the switching sequences and results is shown in Table 2.

Table 2. Inverter Output Voltages

Ro	tor posi	tion	Diode current	VAB	V _{BC}	VCA
Ha	Ha	\mathbf{H}_{c}		101704801400		
1	0	1	$i_{\rm C} \neq 0$	Ede	0	- Edc
			$i_{\rm C} = 0$	Ede	$\frac{1}{2}[-E_{de}+e_{A}+e_{B}-2e_{C}]$	$\frac{1}{2}[-E_{a}-e_{A}-e_{B}+2e_{C}]$
1	0	0	in ≠ 0	0	Edc	- Edc
			$i_{13} = 0$	$\frac{1}{2} \left[E_{de} + e_A + e_C - 2e_B \right]$	$\frac{1}{2} \left[E_{dv} - e_A - e_C + 2e_H \right]$	- Edc
1	1	0	$i_{\Lambda} \neq 0$	- Ede	Ede	Ö
			$i_{\Lambda} = 0$	$\frac{1}{2}\left[-E_{de}-e_{H}-e_{C}+2e_{A}\right]$	\mathbf{E}_{dc}	$\frac{1}{2}\left[-E_{de}+e_{H}+e_{C}-2e_{A}\right]$
0	1	0	$i_{\rm C} \neq 0$	- Ede	0	Ede
			$i_{\rm C} = 0$	- E _{de}	$\frac{1}{2} \left[E_{de} + e_A + e_B - 2e_C \right]$	$\frac{1}{2} \left[E_{de} - e_A - e_B + 2e_C \right]$
0	1	1	$i_{\mathbf{B}}\neq 0$	0	- E _{dc}	Ede
			$i_B = O$	$\frac{1}{2}\left[-E_{de}+e_{c}+e_{A}-2e_{B}\right]$	$\frac{1}{2}\left[-E_{dc}-e_{c}-e_{A}+2e_{B}\right]$	\mathbf{E}_{dc}
0	0	1	$i_A \neq 0$	E _{de}	- E _{de}	1. 0
			$i_{\Lambda} = 0$	$\frac{1}{2} \left[E_{de} - e_{\mu} - e_{e} + 2e_{\lambda} \right]$	- E _{dc}	$\frac{1}{2} \left[E_{de} + e_{\mu} + e_{c} - 2e_{\lambda} \right]$

Table 2. Inverter Output Voltages

3. Open Loop Simulation and Result

Study of electric motor drives system requires the proper selection of a simulation tool. SIMULINK is a toolbox expansion of the MATLAB program. Simulink has the advantages of being capable of complex dynamic system simulations, graphical surrounding with visual real time programming and broad selection of tool boxes. In this section we focus on the Open loop simulation and its result.



Figure 3. Logic circuit for gate signals.

Parameters of the BLDC motor considered for simulation: DC Voltage = 310VRPM = 4600rpm (481.7rad/sec) Moment of Inertia J(Kgm²)= 0.00018 Resistance Ra (ohm/Phase) = 1.535Inductance La (mH /Phase) = 3.285Poles (P) = 4Frequency (Hz) = 50

The simulink model of logic circuit for gate signals shown in Figure 3, has been developed with the help of rotor position (Hall sensor output) shown in Table 1. Figure 4 and 5 shows the torque and speed v/s time waveform for open loop speed control whereas, Figure 6-8 shows the Back-EMF, Line current and DC-Link v/s time waveform for open loop speed control in presence of disturbances.



Figure 4. Torque v/s Time waveform for open loop (X-axis represents Time; Y-axis represents Toque in Nm).



Figure 5. Speed v/s Time waveform for open loop (X-axis represents Time; Y-axis represents Speed in rpm).



Figure 6. Back-EMF v/s Time waveform for open loop (X-axis represents Time; Y-axis represents Back-EMF in volt).



Figure 7. Line Current v/s Time waveform for open loop (X-axis represents Time; Y-axis represents Current in Amp).



Figure 8. DC-Link Current v/s Time waveform for open loop (X-axis represents Time; Y-axis represents Current in Amp).

From Figure 4 and 5, it can be observed that when load is applied the torque increases and the speed gets reduced but doesn't track the reference speed in case of open loop control. Closed loop control is therefore required for accurate tracking of reference speed in presence of load disturbances.

4. Controller Design

Controller is a device which monitors and alters the operating conditions of a given dynamical system. The control algorithms are usually divided into two main types: Open-loop and Closed-loop.

A. PID Controller

The PID controller has been widely used in industrial applications owing to its simplicity, robustness, reliability and easy tuning parameters. PID commonly interpreted as Proportional, integral and Derivative controller possesses the following properties:

Controller	Response time	Overshoot	Error
Proportional (P)	Small Large		Small
Integral (I)	Decrease	Increase	Zero
Derivative (D)	Increase	Decrease	Small Change

The typical structure of PID control with unity feedback is shown in Figure 9. The



Figure 9: Diagram of a PID control system.

PID controller minimizes the error value by adjusting the control variable, such as Position and Speed etc. The transfer function of the PID controller can be represented as

$$G_{C(PID)}(s) = \frac{U(s)}{E(s)} = \left[K_{P} + \frac{K_{I}}{s} + K_{D}s\right]$$
 -----(13)

where, U(s) - Control variable

- E(s) Error signal
- K_{P} Proportional Constant
- K_{I} Integral Constant
- K_D Derivative Constant

The closed loop transfer function of the plant (BLDC Motor) with PID controller shown in Figure 9 is

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where, $G_{P}(s)$ - Plant transfer function

B. Modified PID Controller

In this controller, only Integral term is connected in feed forward path and Proportional with Derivative terms is applied to the output of the plant and is fed to the negative part of the comparator of the inner loop. This negative feedback minimizes the initial overshoot that happens in case of conventional PID. The integral term present in the feed forward path helps the system to reach the steady state. This type of response can be considered as little sluggish system without steep overshoots. The typical structure of Modified PID control with unity feedback is shown in Figure 10.



Figure 10. Diagram of a Modified PID control system.

The transfer function of the Modified PID controller can be represented as

$$G_{C(Modified PID)}(s) = \frac{U(s)}{E(s)} = \frac{\frac{K_{I}}{s}}{1 + [K_{P} + K_{D}s].G_{P}(s)} - \dots - (15)$$

The closed loop transfer function of the plant (BLDC Motor) with Modified PID controller shown in Figure 10 is

C. Finalization of K_P , K_I and K_D

The transfer function of the Plant (BLDC Motor) is

where, J - Moment of Inertia (Kgm²)

 B_V - Viscous Friction Coefficient (Nms/rad)

- R Resistance (Ω /Phase)
- L Inductance (mH/Phase)
- K_e Back-EMF Constant (V/Krpm)
- K_{T} Torque Constant (Nm/A)
- ω Angular Velocity of rotation (rad/sec)
- E_{dc} DC-link Voltage (V)

The characteristics equation or the denominator of the closed loop transfer function of the system with PID is similar to that of the modified PID controller. So, the value of control parameters (i.e, Kp, K_I and K_D) will be the same. The characteristics equation will be

$$1 + G_{C(PID / Modified PID)}(s) \cdot G_{P}(s) \cdot H(s) = 0$$

where, H(s) = 1 (unity feedback) $\begin{bmatrix} I \\ I \end{bmatrix} S^{3} + \begin{bmatrix} I \\ P \end{bmatrix} + \begin{pmatrix} I \\ P \end{bmatrix} + \begin{pmatrix} K \\ K \end{bmatrix} \begin{bmatrix} S^{2} + \begin{bmatrix} P \\ P \end{bmatrix} + \begin{pmatrix} K \\ K \end{bmatrix} + \begin{pmatrix} K \\ K \end{bmatrix} \begin{bmatrix} K \\ K \end{bmatrix} = 0$

$$[J.L].S^{+} + [(J.K) + (L.B_{V}) + (K_{T}.K_{D})].S^{+} + [(R.B_{V}) + (K_{T}.K_{e}) + (K_{T}K_{P})].S^{+} + [K_{T}K_{T}] = 0$$

$$\therefore S^{3} + \frac{[(J.R) + (L.B_{V}) + (K_{T}.K_{D})]}{[J.L]}.S^{2} + \frac{[(R.B_{V}) + (K_{T}.K_{e}) + (K_{T}K_{P})]}{[J.L]}.S^{+} + \frac{[K_{T}K_{T}]}{[J.L]} = 0 - (18)$$

Desired specifications for the closed loop control are: Damping factor (ζ) = 0.7 Settling time (Ts) \leq 1sec According to these specification, dominant poles have been found to be at $S_{1,2} = -4 \pm 4.0808i$

Since, the characteristic equation of the plant with PID and Modified PID controller is of the third order (equation (18)), so the placement of the third pole (a) is quite necessary. According to the dominant pole concept, the third pole can be placed quite far away from the real part of the dominant poles so as to have minimal impact on overall closed loop transient response.

Using pole placement concept, the characteristic equation can be written as

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Using R-H criteria, the values of KP, KI and K should be positive. The value of alpha ($\bar{\alpha}$) is taken in such a way that the control parameters should be positive and the value of ζ should be less than or equal to 1. Compare and substitute all the motor and control parameters in equation (18) and (20), we obtain

Parameter	Value
K _P	0.4638
K _I	3.9404
K _D	0.1201

The parameters of the controller and the motor are substituted in the closed loop simulink model and responses obtained are discussed in section 5.

5. Simulation Result for Closed Loop control of BLDC Motor Drives using PID and Modified PID controller

The closed loop simulation with PID and Modified PID controller ss carried out employing the following steps:

- i) Design Of Three Phase Inverter Using Power MOSFET (IRF 460).
- ii) Utilizing the BLDC Motor Parameters in Simulation Available in the Electric Drives laboratory Of BIT Mesra, Ranchi.
- iii) The Resultant Speed Values Is Fed Back and Compared with the Reference Speed and the Error generated is fed into the PID/Modified PID Controller.
- iv) The Output of the Controller Regulates the Gate Pulse of the Semi converter.
- v) The Output of the Semi converter serves as the Dc-Link Voltage for Three Phase VSI.

The torque v/s time, speed v/s time, line current v/s time and voltage v/s time waveform obtained in closed loop simulation with PID and Modified PID controller is shown in Figure 12-17.



Figure 11. Torque v/s Time waveform for closed loop with initial overshoot (X-axis represents Time; Y-axis represents Torque (Nm)).



Figure 12. Speed v/s Time waveform for closed loop (X-axis represents Time; Y-axis represents Speed (rad/sec)).



Figure 13. Speed v/s Time waveform for closed loop with rise time and settling time (X-axis represents Time; Y-axis represents Speed (rad/sec)).



Figure 14. Line Current v/s Time waveform for closed loop (X-axis represents Time; Y-axis represents Current (Amp)).



Figure 15. Output Voltage v/s Time waveform for closed loop (X-axis represents Time; Y-axis represents Voltage (volt)).



Figure 16. DC-Link Current v/s Time waveform (PID) (X-axis represents Time; Y-axis represents Current (Amp).



Figure 17. DC-Link Current v/s Time waveform (Modified PID) (X-axis represents Time; Y-axis represents Current (Amp).

Controller Type	Rise Time	Settling Time	Overshoot
PID	0.00105 sec	0.3413 sec	7.888%
Modified PID	0.39285 sec	0.6772 sec	0%
Fuzzy PI [14]	-	1.01 sec	0%
FOPID [13]	1.168332 sec	1.882497 sec	0%

Table 3. Comparison of transient responses of speed with PID and Modified PID Controller

Table 4. Comparison of Maximum Overshoot in case of PID and Modified PID Controller

Output Parameters	PID (Max. Peak Value)	Modified PID (Max. Peak Value)
Torque	98.89 Nm	0.4283 Nm
Speed	519.7 rad/sec	-
Line Current	82.44 A	0.02692 A
DC-Link Current	Very high	2.552 A

From Table 3, it can be observed that overshoot in speed using PID controller is high compared to that of Modified PID. Even if rise time and settling time is better in case of conventional PID, but the fact that overshoot is more overshadows the other transient performance parameters. In Fuzzy, Fuzzy-PI [14] and FOPID [13] controller parameters are computed separately which leads to modification in the assembly of hardware components. In this paper, the controller parameters are not varied for conventional and Modified PID. Thus, for the same set of controller parameters the hardware components can be assembled to examine the transient response characteristics.

Table 4, discusses about the maximum peak values for torque, speed, line current and dclink current with PID and Modified PID controller. From Table 4, it can be observed that the starting torque in case of PID controller is very high. As a result the starting current is high enough to damage the motor winding. Modified PID controller makes the system response little sluggish as the starting torque is comparatively very low. Therefore, the stating current is quite low resulting into safe operation of motor.

6. Conclusion

In this paper, a BLDC Motor with three phase inverter has been simulated for 120 degree mode of conduction using Hall sensor. The controllers (PID and Modified PID) are designed and simulated for closed loop operation of BLDC motor. The simulation result indicates that the peak overshoot get reduced when the modified PID controller is used and gives better response in both no load and full load conditions compared to PID controller.

Future Aspect: The Hardware assembly of Open loop has already been implemented and its transient response has been obtained. As far as the closed loop is concerned, the hardware for the PID and Modified PID controller is in progress. Non-linear and advanced controller design methods employing the concepts of sliding mode controller and feedback linearization can be implemented for closed loop speed control. Hardware development of motor and controller configuration can be designed to verify the simulink result.

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