COMPARATIVE STUDY OF CLOSED LOOP MODEL OF BLDC MOTOR WITH DIFFERENT CLASSICAL CONTROLLER

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ABSTRACT:
A Brushless DC Motor (known as BLDC) is a Permanent Magnet Synchronous Electric motor which is driven by direct current (DC) electricity and it accomplishes electronically controlled commutation system instead of a mechanically commutation system. In this paper, Closed Loop Control system of BLDC motor drives using different combination of classical controller is presented. MATLAB Simulation is done for various combination of classical controller and their performances are compared to find out the best combination. Moreover, Frequency Analysis using Fast Fourier Transform is also done to know the controller behavior and to calculate the current THD (Total Harmonic Distortion) to confirm the best combination for the system. The main objective of this study is to confirm the best combination of classical controllers.

KEYWORD: BLDC motor, Closed loop, Classical Controller, Frequency Analysis, Simulation.

I: INTRODUCTION

Brushless DC motors (BLDC) has many applications in industries due to their high power density and ease of control. Since BLDC motor does not have brush, it has - longer life, higher efficiency, higher speed and maintenance free. Therefore, BLDC Motors become very popular in modern drive technology. They gain popularity rapidly in the fields of Consumer Appliances, Automotive Industry, Industrial Automation, Chemical and Medical, Aerospace and Instrumentation and the range is increasing day by day. The ratio of Torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors [1 - 15].

Stator and Rotor are the main part of the BLDC motors like Brush DC motor. Hall sensor may be considered as one part of BLDC motor since most of them are sensor by Hall Effect signal. Hall sensors work on the hall-effect principle that when a current carrying conductor is exposed to the magnetic field, charge carriers experience a force based on the voltage developed across the two sides of the conductor. If the direction of the magnetic field is reversed, the voltage developed will reverse as well. For Hall-effect sensors used in BLDC motors, whenever rotor magnetic poles (N or S) pass near the hall sensor, they generate a HIGH or LOW level signal, which can be used to determine the position of the shaft. There are single-phase, 2-phase and 3-phase configurations, Out of these, 3-phase motors are the most popular and widely used. The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery. The rotor is made of permanent magnet and can vary from two to eight pole pairs with alternate North (N) and South (S) poles. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor [1, 6, 10, 11, 12].

The brushless motors are generally controlled using a three phase power semiconductor bridge. The motor requires a rotor position sensor for starting and for providing proper commutation sequence to turn on the power devices in the inverter bridge. Based on the rotor position, the power devices are commutated sequentially every 60 degrees. Instead of commutating the armature current using brushes, electronic commutation is used that is why it is called as an electronic motor.

For Each commutation sequence, one winding is energized to positive, the other winding is energized negative and the next is in a non-energized condition. Torque is produced due to the interaction between the two magnetic fields generated by the stator coils and the permanent magnets. Ideally, the peak torque is observed when these two fields are in quadrature to each other. In order to keep the motor running, the magnetic field generated by the windings should shift their position, as the rotor moves to catch up with the moving stator field [1, 2, 10].

In case of Closed loop control, feedback is given from the output to get the desired speed. The main advantages of this method are the system stability; minimal disturbances compared to open-loop control and reduced sensitivity for dynamic load variations. Normally, there are two loops for feedback; the outer loop is use for speed or voltage control and the inner loop is use for torque or current control. Desire speed or Reference Speed is given as the input which is compare with the output speed, if there is any difference between the two, it will be treated as an error and it will be minimized by the controller so that the output will be same as the reference speed. So, the output is depending on the reference speed and the controller, it is independent of the applied voltage which is fixed at a particular value. Generally, classical controller such as PID, PI and P controller are used for controller. [1, 6, 8]

PID CONTROLLER: PID controller may be the most generally utilized within closed-loop control system. This controller is the most reliable, accurate and provides better system stability i.e. less steady state error response as well as it helps to eliminate incoming error to zero with minimum iterations. The three part of PID controller act as follow: (a) System rise time will be reduced by K_p, it provides faster response in variable load condition. (b) Steady state error will be reduced by K_i, hence the motor speed is pushed near to reference speed. (c) Settling time and oveshoot will be reduced by K_d, hence provide faster response. The continuous control signal u(t) of the PID controller is presented in the following equation [11]:

$$u(t)= K_p * e(t) + K_i \int_0^t e(t)\,dt + K_d * e(t) \qquad \text{(i)}$$

PI CONTROLLER: PI controller is an accurate and provides good system stability i.e. less steady state error response. But the integral factor in controller takes more iteration to reduce error to zero. This controller is fundamentally used to limit the steady state error coming about because of P-controller hence it is important to blend the proportional and integral to increase the speed of response. The PI controller can be used to control speed as well as torque or current of BLDC motor. The Effects of PI parameters are: (a) Improve Damping. (b) Zero offset (c) Decrease/ No steady state error. The speed/position encoder is utilize to obtain running speed of brushless DC motor and compare it with the reference value and the resulting difference is examined by PI-controller which is governed by using the equation below [11].

$$u(t) = K_p * e(t) + K_i \int_0^t e(t)\, dt \qquad \text{(ii)}$$

P CONTROLLER: A proportional or P-Only controller is the simplest algorithm in the PID family. Proportional Controller is a type of linear feedback control system in which a correction is applied to the controlled variable which is proportional to the difference between the desired value (set point, SP) and the measured value (process variable, PV).The gain K_p is used in P controller and output produced that is inversely relative to steady state error so the system becomes unstable if the gain K_p is high. P controller is directly proportional to incoming error; hence a little change in error can cause system instability. The following equation used to govern Proportional (P) controller [11]

$$u(t) = K_p\, e(t) \qquad \text{(iii)}$$

Where u(t): signal of actuating
e (t): signal of error
K_p: constant of proportional gain

PID parameters Proportional gain Kp, Integral Gain Ki, and Derivative Gain Kd affects system's overall performance. Hence choosing right parameters for a system is a difficult process and can be done by using several tuning methods which includes manual tuning, Ziegler-Nicholas, Particle Swarm, Ant Colonization, Genetic Algorithm and Cohen-coon tuning. The advantage of Classical controller is its feasibility and stability, simple and easy to be implemented and adjusted. The PID gains can be designed based upon the system parameters if they can be achieved or estimated precisely. Without creating mathematical model of the system, it can still be used by tuning it with trial and error. They are not heavy on hardware; therefore it can be implemented on cheap hardware also. If once designed, then its further tuning does not require skilled personnel. Moreover, the PID gain can be designed just based on the system tracking error and treats the system to be "black box" if the system parameters are unknown. [1, 6, 11]
The block diagram of Closed Loop Control is shown in Fig. 1. It has five main blocks such as Voltage Source, Inverter, Motor, Speed Controller and Torque Controller.

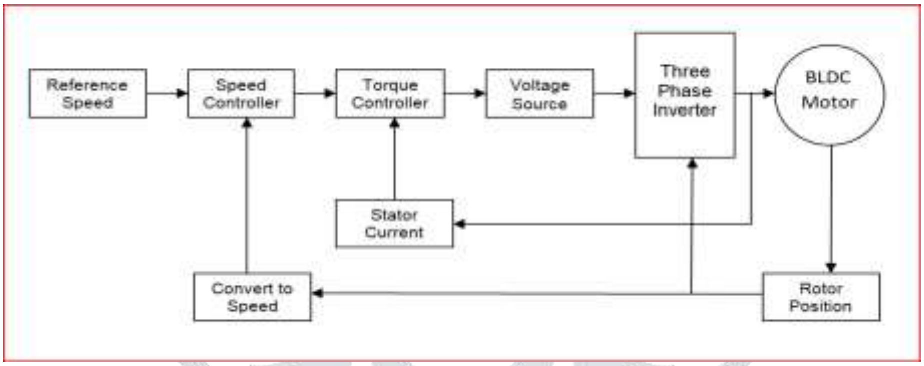

Fig. 1: Block Diagram of Closed Loop Control of BLDC motor

II: MATHEMATICAL MODELLING

In modeling a BLDC motor a, b, c, phase variable model is preferred as the mutual inductance between stator and rotor is non-sinusoidal. Before formulating the equations following assumptions are made in modeling the BLDC motor.

- The motor is not saturated.
- Resistances of all the stator windings are equal, self and mutual inductances are constant.
- The power semiconductor devices are ideal.

There are two possible methods to model a BLDC motor, one is a, b, c phase variable model and the other is d-q axis model. BLDC motor has the permanent magnet with trapezoidal back EMF whereas synchronous motor has sinusoidal back EMF. So transforming to d-q axis does not provide any added benefit, thus a, b, c phase variable model is chosen. The equivalent diagram of the BLDC motor is as shown in the fig.2 [3, 5, 8, 12].

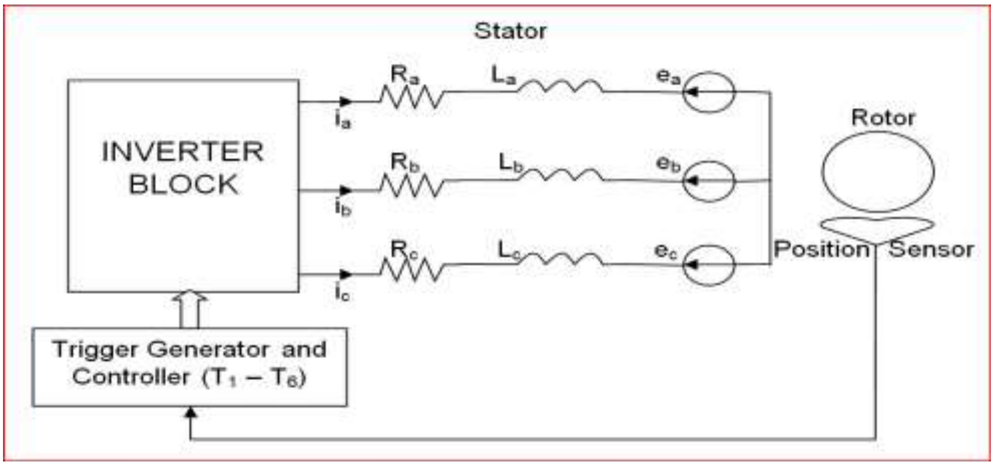

Fig.2: Three-phase BLDC motor equivalent circuit.

The voltage equations of BLDC motor are:

$$V_a = R_a i_a + L_a \frac{d}{dt} i_a + e_a \quad (1)$$

$$V_b = R_b i_b + L_b \frac{d}{dt} i_b + e_b \quad (2)$$

$$V_c = R_c i_c + L_c \frac{d}{dt} i_c + e_c \quad (3)$$

where, $L_a = L_b = L_c = L$, are the self inductance [H].
V_a, V_b, V_c, are the per phase stator voltages [V].
$R_a = R_b = R_c = R$ are the per phase stator resistance [Ω].
i_a, i_b, i_c, are the per phase stator currents [A].
e_a, e_b, e_c, are the induced back-emf [V].

In the 3-phase BLDC motor, the back-EMF is related to a function of rotor position and the back-EMF of each phase has 120º phase angle difference so equation of each phase should be as follows:

$$e_a = \frac{Ke}{2} * F(\theta_e) * \omega_r(t) \quad (4)$$

$$e_b = \frac{Ke}{2} * F\left(\theta_e - \frac{2\pi}{3}\right) * \omega_r(t) \quad (5)$$

$$e_c = \frac{Ke}{2} * F\left(\theta_e + \frac{2\pi}{3}\right) * \omega_r(t) \quad (6)$$

where, K_e is the back emf constant of one phase [V/rad.s^{-1}]
ω_r is the mechanical speed of the rotor [rad.s^{-1}]
θ_e is electrical rotor angle [° elect.]

The electrical rotor angle is equal to the mechanical rotor angle θ_m multiplied by half of the number of poles P :

$$\theta_e = \frac{P}{2}\theta_m \quad (7)$$

The function $F(\theta_e)$ gives the trapezoidal waveform of the back – emf. One period of this function can be written as follow:

$$F(\theta_e) = \begin{cases} 1 & 0 < \theta e < \frac{2\pi}{3} \\ 1 - \frac{6}{\pi}\left(\theta e - \frac{2\pi}{3}\right) & \frac{2\pi}{3} < \theta e < \pi \\ -1 & \pi < \theta e < \frac{5\pi}{3} \\ -1 + \frac{6}{\pi}\left(\theta e - \frac{2\pi}{3}\right) & \frac{5\pi}{3} < \theta e < 2\pi \end{cases} \quad (8)$$

The Electromagnetic Power equation is:

$$P_e = (e_a i_a + e_b i_b + e_c i_c) \quad (9)$$

By neglecting the stray and mechanical losses; the electromagnetic power is completely converted to kinetic energy, so

$$P_e = T_e \omega_r \quad (10)$$

Therefore electromagnetic torque equation is:

$$T_e = \frac{1}{\omega r}(e_a i_a + e_b i_b + e_c i_c) \quad (11)$$

Also, $$T_e = \frac{Kt}{2}\left[F(\theta_e) i_a + F\left(\theta_e - \frac{2\pi}{3}\right) i_b + F\left(\theta_e + \frac{2\pi}{3}\right) i_c\right] \quad (12)$$

where, T_e is the electromagnetic torque
K_t is torque constant

The equation of mechanical part (equation of motion) is:

$$J\frac{d}{dt}\omega_m + B\omega_m = T_e - T_l \quad (13)$$

where, B is friction coefficient [Nms.rad^{-1}].
J is moment of inertia of rotor and coupled shaft [kgm^2].
T_l is load torque [Nm].
ω_m is rotor speed [rad.s^{-1}].

III: SIMULATION RESULT AND DISCUSSION

The simulation is done using MATLAB R2018b with Auto (Automatic solver selection) Variable-step type solver. The simulation time is 2 second. The simulink model is shown in Fig. 3. The BLDC Motor block is taken from Sim-Power System tool box and configurations are altered as Trapezoidal back EMF and the BLDC motor parameter is set as given in Table 1 below:

Parameter types	Values	Units
Stator phase Resistance	2.8750	Ohm
Stator phase inductance	8.5e-3	H
Flux linkage established by magnet	0.175	V.s
Voltage constant	146.6077	V
Torque constant	1.4	N.m
Back EMF flat area	120	Degree
Inertia	0.8e-3	J(kg.m^2)
Viscous damping	1e-3	F(N.m.s)
No. of Pole pairs	4	
Static friction	0	TF(N.m)

Table 1: BLDC motor Parameter

The inverter is configured from universal bridge of Sim-Power System tool box and the configuration parameters are: Snubber resistance R_s is 5000 ohms; Snubber Capacitance C_s is 1e-6F; R_{on} is 1e-3 ohms; choosing the MOSFET as switches.

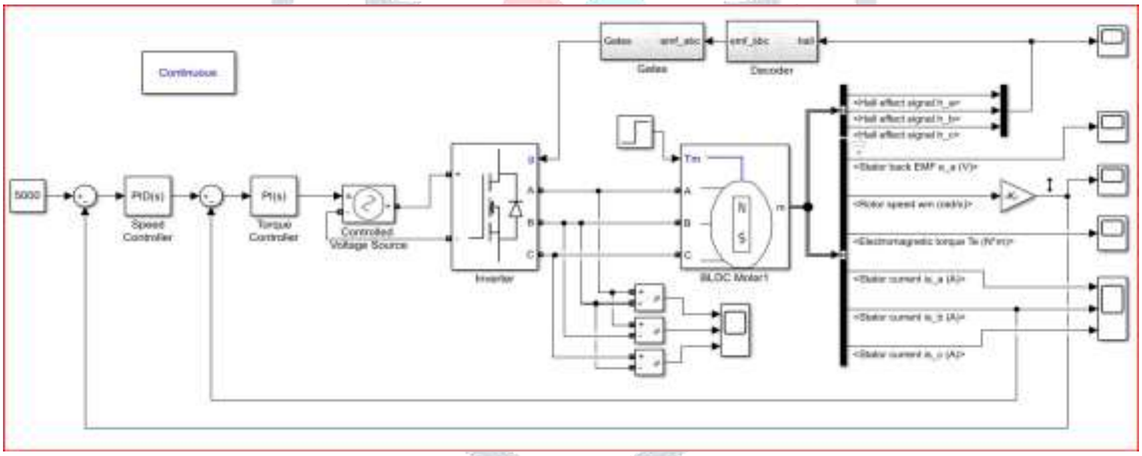

Fig. 3: Simulink Model of Closed Loop Control of BLDC motor

As shown in simulink model in Fig. 3, the Controller for Speed as well as for Torque or Current can be P or PI or PID controller. So, different types of combinations can be chosen. Therefore, to verify the best combination of the classical controller different combinations is performed and the results obtain are tabulated in Table 2 when the input voltage is 200V and Reference speed is 3000 RPM. The various parameters are recorded after manually tuning the controller to achieve the best waveform, and adjustment is done to get same type of waveform in each combination so that each combination can be compared meaningfully.

Parameter of Speed Controller	Parameter of Current Controller	+Overshoot (in %)	Rise time (in ms)
	P & P Combination		
P=4	P=3	88.777	0.0343
	PI & P Combination		
P=0.1; I=4	P=1	0.993	124.925
	PI & PI Combination		
P=0.1; I=9	P=1; P=1	0.505	44.034
	PID & P Combination		
P=0.1; I=12; D=0.001	P=1	0.505	36.528
	PID & PI Combination		
P=12; I=5; D=0.01	P=0.1; I=1	0.499	33.617

Table 2: Step response of various combinations.

The Speed response of each combination at 200V input supplies by giving reference speed of 3000 RPM are given below (Fig. 4 to Fig. 8). Fig. 9 shows the speed response of various combinations excluding P&P combination which is the worse one.

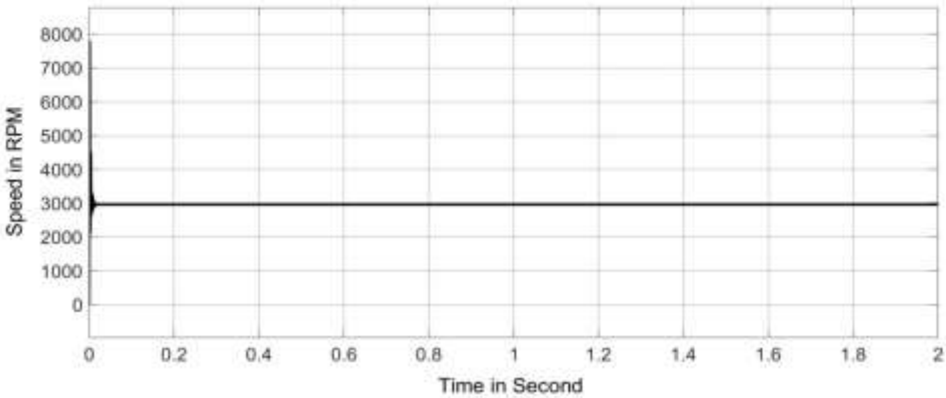

Fig. 4: Speed response of P & P combination.

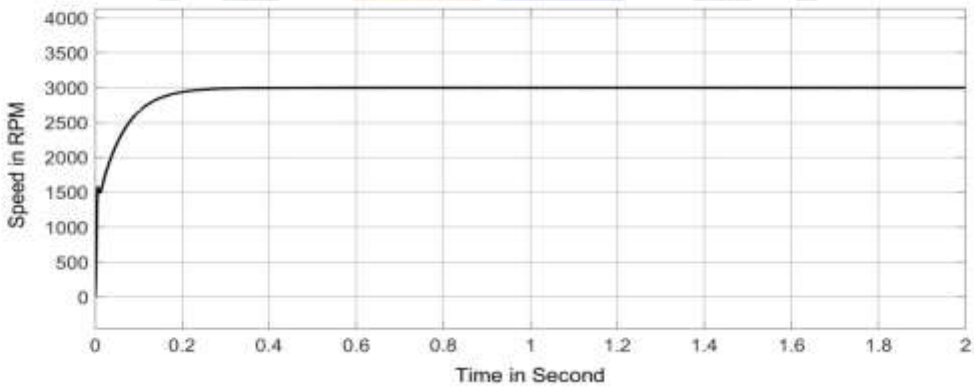

Fig. 5: Speed response of PI & P combination.

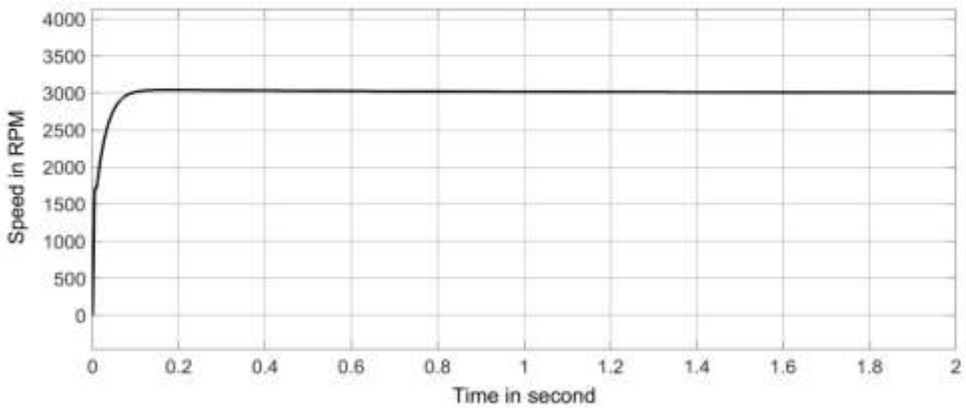

Fig. 6: Speed response of PI & PI combination.

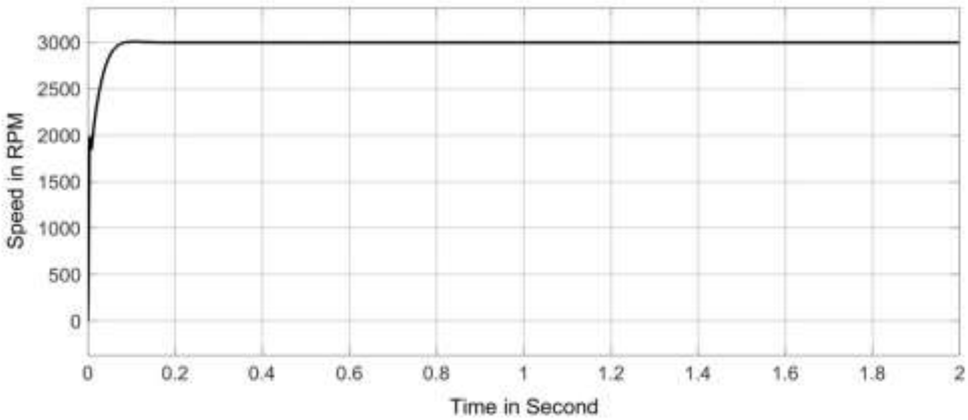

Fig. 7: Speed response of PID & P combination.

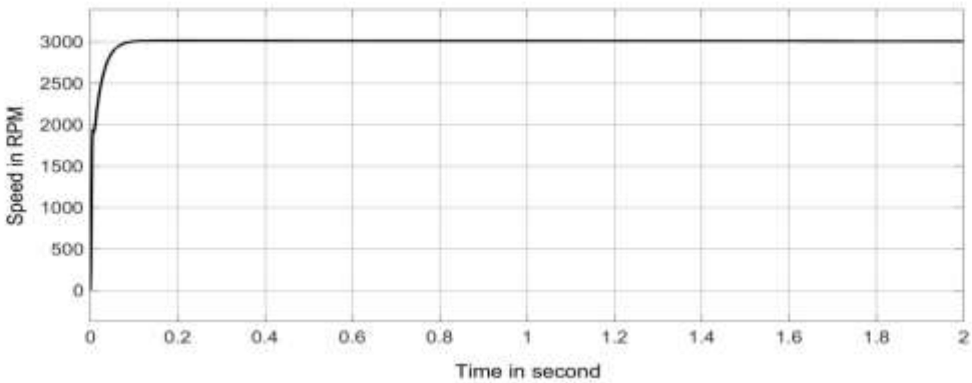

Fig. 8: Speed response of PID & PI combination.

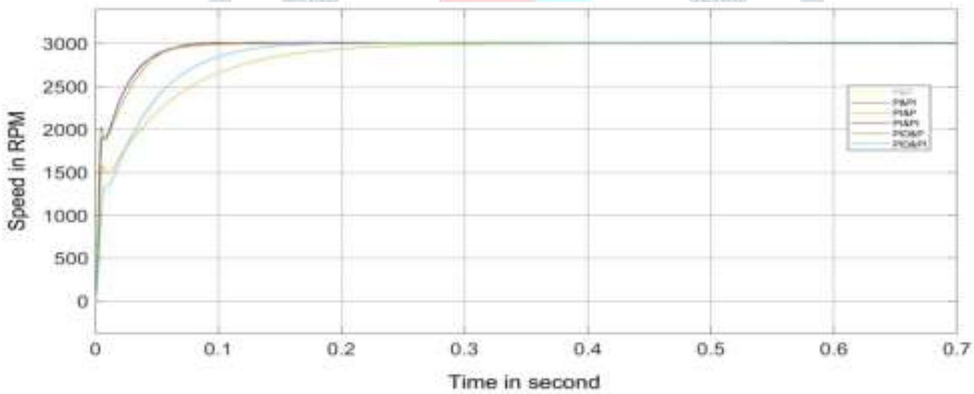

Fig. 9: Speed response of various combinations.

As it can be seen from above waveform, the speed response of various combinations are almost similar except P & P combination which is different from other, so P & P combination is the worse one and can be neglected. And all other combinations can be compared from their step response. As shown in table 2, the overshoot and rise time are least in case of PID & PI combination. Therefore, when PID controller is used as Speed Controller and PI controller is used as Current/ Torque controller, the best performance of the system is achieved.

IV: FREQUENCY ANALYSIS

Frequency Analysis is done for better comparison of those different combinations (the best three combinations are chosen). The BLDC is nonlinear load having non-sinusoidal current and voltage waveform. The current drawn by the BLDC has narrow notches which are the cause of torque ripple and it will produce harmonics in the power line system. Harmonic is a periodic wave component having an integral multiple of the fundamental frequency. Harmonic distortion is a dirty power which is usually linked with industrial plants that used adaptable power supplies, speed drives, and other equipment's which use solid-state switching. Harmonic distortion of voltage and current have existed together (current harmonic distortion causes voltage harmonic distortion). Harmonic distortion increase voltage peaks that make extra stress on motor and wire insulation leads to breakdown and failure. Moreover, harmonics increase RMS current, leads to increase in operating temperature of the motor, thereby reducing its life. Therefore, harmonic distortion should be reduced as far as possible in drive system. Several methods are there to find out total harmonic in the drive system, Fast Flourier Transform is used as it is easy to implement [2, 5].

In this analysis Current Frequency Spectrum is plotted using Matlab Software. FFT (Fast Fourier Transform) Analysis is used and the graph is plotted between Harmonic order versus Percentage of Fundamental Frequency. The Total Harmonic Distortion (THD) of various combinations at 200 V supplied is tabulated in table 4 below.

Combinations	Operation Frequency (Hz)	Current THD (%)
PI & PI	185	111.16
PID & P	183	118.28
PID & PI	190	84.30

Table 3: Current THD and Operation Frequency at various Load conditions.

Fig. 10 to Fig. 12 show Phase Current (I_a) Frequency Spectrum of different combinations at 200 V supply voltage by giving reference speed of 3000 RPM.

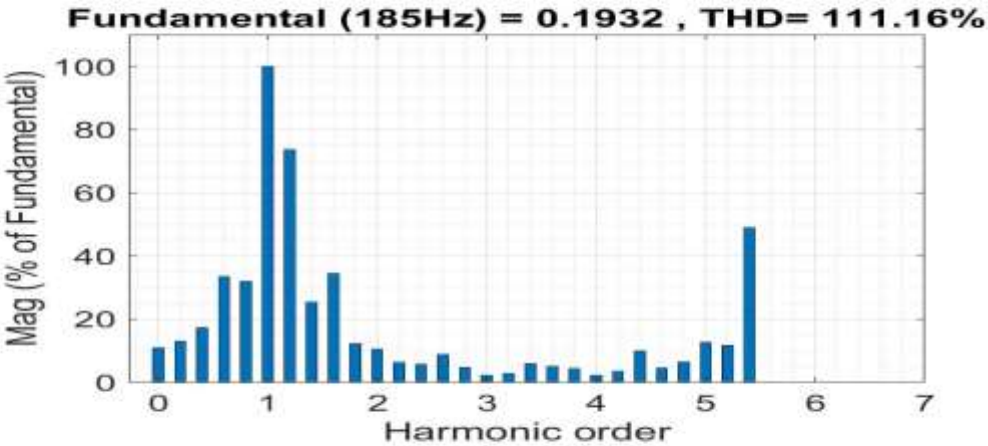

Fig. 10: Frequency Spectrum of Current of PI & PI combination.

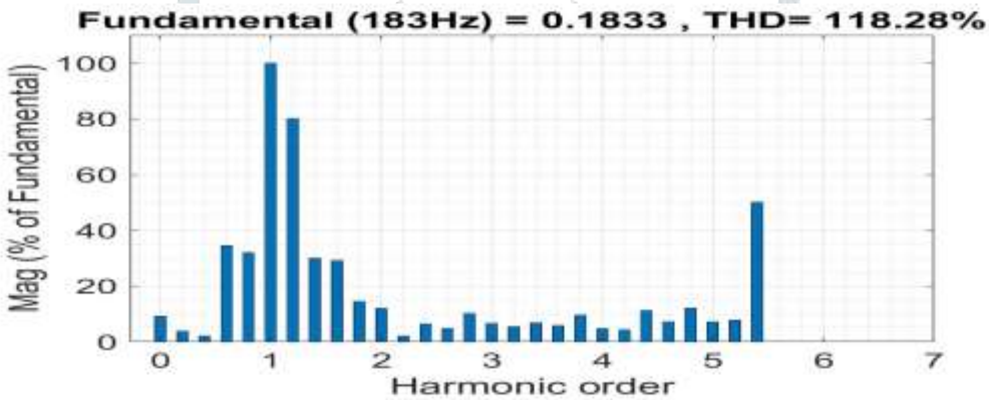

Fig. 11: Frequency Spectrum of Current of PID & P combination.

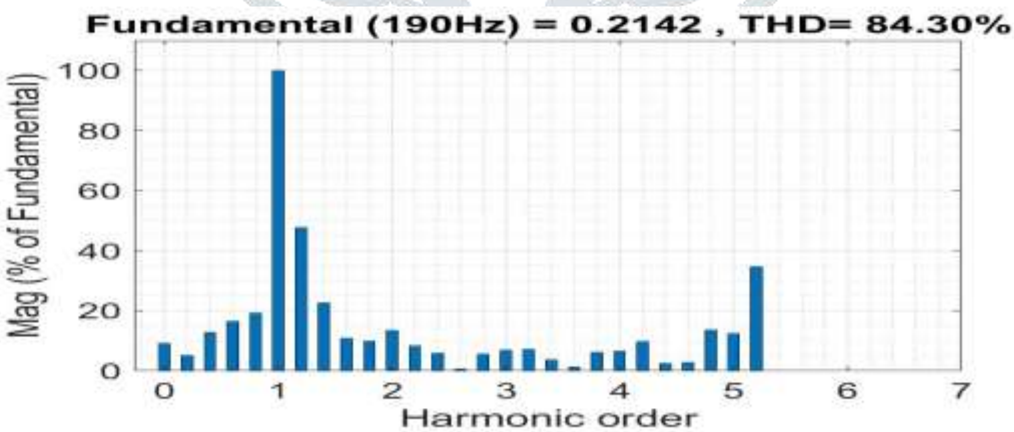

Fig. 12: Frequency Spectrum of Current PID & PI combination.

As it can be seen from above observation, in case of PID & PI combination the current THD is least. This proved that PID & PI combination, where PID controller is used as Speed Controller and PI controller is used as Current/ Torque controller is the best choice for the system.

V: CONCLUSION

In this paper, the closed loop control of BLDC using different combinations of classical controller is performed. Their performance are compared to find out that PID & PI combination, where PID controller is used as Speed Controller and PI controller is used as Current/ Torque controller give the best performance. The Frequency analysis is implemented using FFT analysis in the best three combinations and found out that the current THD is least in case of PID & PI combination which support the previous observation and proved that this combination is the best combination for the system.

REFERENCES

[1] Chang-liang Xia, “Permanent Magnet Brushless DC Motor Drives and Control”, John Wiley & Sons, First Edition, ISBN 978-1-118-18833-0, 2012.
[2] Stefan B., “BLDC motor modelling and control a Matlab/ Simulink implementation”, Master thesis in Electrical Power Engineering, Chambers University of Technology, Gothenburg. Sweden, (May 2005).
[3] Shirish Vasantrao Gadewar and A.M.Jain, “Modelling and Simulation of Three Phase BLDC motor for Electric Braking using Matlab/ Simulink”, International Journal of Electrical, Electronics and Data Communication, pp 48-53, July 2017.
[4] Vinod KR Singh Patel and A.K.Pandey, “Modeling and Performance Analysis of PID Controlled BLDC Motor and Different Schemes of PWM Controlled BLDC Motor”, International Journal of Scientific and Research Publications, pp 1-14, Volume 3, Issue 4, April 2013.
[5] Adel A. Obed and Abbas K. Kadhim, “Speed and Current Limiting Control Strategies for BLDC Motor Drive System: A Comparative Study”, International Journal of Advanced Engineering Research and Science (IJERS), pp 129-130, Vol-5, Issue-2, Feb 2018.
[6] Hayder Salim Hameed, “Brushless DC motor controller design using MATLAB applications” IEEE, 1st International Scientific Conference of Engineering Sciences, pp 44-49, 2018.
[7] M. Vignesh kumar, “Speed Control Of Three Phase BLDC Motor Using Four Switch Inverter”, International Journal of Scientific & Engineering Research, pp 351-356, Volume 4, Issue 5, May-2013
[8] Manjusha D. Hedau and K. N. Sawalakhe and R. G. Shrivastava, “Performance Improvement of BLDC Motor with Hysteresis Current Controller Topology”, International Journal of Engineering Research and Technology, pp 24-36, Vol-4, Issue-30, Special Issue 2016.
[9] SK.Sharmila, K.Esther Rani, A.Anil Kumar and T.Naveen, “Comparison of different Control Strategies for BLDC motor Drive”, International Journal of Electrical Engineering and Technology, pp 24-36, March-April 2018.
[10] Anurak Dwivedi, A.N.Tiwari, “A Review: Speed control of brushless DC motor” IJBSTR Review Paper, Vol. 1, Issue-6, June 2013.
[11] Lokesh Kumar Agrawal and Bhavesh Kumar Chauhan and G. K. Banerjee
“Speed Control of Brushless DC Motor Using Conventional Controllers” International Journal of Pure and Applied Mathematics, pp 3955-3961, Volume119, No.16, 2018
[12] MS. Juli Singh, “Analysis the speed control of BLDC drive using sensors”, International Journal of Engineering Research and Applications, pp 2868-2884, Vol.-2, Issue-3, May-June 2012.
[13] Ravi Maraviya, “Simulation and Analysis for Different Speed Control Methods of BLDC Motor Drive”, International Journal of Advance Research in Engineering, Science & Technology, pp 677-682 , Volume 4, Issue 4, April-2017.
[14] Anjali Hingmire and B.B. Pimple, “Simulation and Analysis Studies of Speed Control of Brushless DC Motor Using Hall Sensors”, International Conference on Smart Electric Drives & Power System, 2018.
[15] Nguyen Thi Thanh Nga, Nguyen Thi Phuong Chi and Nguyen Hong Quang, “Study on Controlling Brushless DC Motor in Current Control Loop Using DC-Link Current”, American Journal of Engineering Research (AJER), Volume-7, Issue-5, pp-522-528, 2018.