

Cascade control of BLDC motor drive using MOMI tuning method

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Abstract

This paper presents a new design concept for cascade control of brushless direct current (BLDC) motor drive. Cascade controllers are designed for definite separation of loops. This separation allows independent design of controllers with minimum interaction among loops. The resultant structure with inner loop and outer loop is a robust structure. Magnitude Optimum Multiple Integration (MOMI) tuning method is proposed to design the PID controllers used in inner and outer loops. This method provides a fast and non-oscillatory closed-loop response for motor drives. The aim of the proposed method is to determine optimal Proportional-Integral-Derivative gains of the controller so as to force the rotor to follow the reference speed without any oscillations with zero steady-state error. MOMI method proceeds by determining the open-loop process gain to calculate the moments (areas), from which controller parameters can be calculated. The MATLAB/SIMULINK is used for simulation of the drive system. Several simulation tests performed to investigate the robustness of the controller and is justified by the simulation of BLDC drive under set-point changes, input disturbance and load disturbances.

Keywords: BLDC motor; MOMI; PID controller; Trapezoidal back emf; Cascade control

Introduction

BLDC motor has wide range of applications because of its advantages such as high efficiency, flat speed-torque characteristics, and high speed range, smaller in size and lighter, longer life, low noise and good dynamic response when compared against brushed direct current motor. Both, DC brushed and brushless motors contain a combination of Permanent magnet and electromagnetic fields, which produce torque resulting in motion. In a brushless DC motor, the rotor consists of magnets and stator contains the windings and no brushes present as name suggests. Commutation is implemented electronically in brushless motors using semiconductor switches to change current in the windings based on position of rotor [1]. The BLDC motor is an equivalent reversed DC commutator motor, as its magnet rotates while the conductors remain stationary, this facilitates the external or internal position sensors in BLDC motors to sense the actual rotor position. The rotor position position can also be sensed by measuring

the changes in back emf, which is sensorless control [2]. As sensors cannot be used in all applications, the back emf method of commutation is used to simplify the motor construction and can reduce the cost of the motor.

This paper provides an approach for application of PID controllers in cascade control of BLDC motor drive system. The cascade control configuration consists of two loops. The inner loop is called current control loop (secondary loop) and outer loop is called speed control loop (primary loop). Each loop is associated with its PID controller. Therefore, it is complicated design than that of single loop controller. A new method, Magnitude optimum multiple integration (MOMI) is proposed for tuning two controllers in cascade control system.

Blde Motor Model

The stator windings of BLDC motor should be energized in a sequence to rotate the motor, to understand which winding to be energized following the energizing sequence, It is important to know the position of rotor. Rotor position is sensed by measuring the changes in the back emf. With this type of commutation, Hall sensors can be eliminated which simplifies the construction of motor and reduces the cost as well [3][4].

$$V_{an} = R_a i_a + \frac{d}{dt} (L_{aa} i_a + L_{ba} i_b + L_{ca} i_c + e_a)$$

$$V_{bn} = R_b i_b + \frac{d}{dt} (L_{ab} i_a + L_{bb} i_b + L_{cb} i_c + e_b) \quad (1)$$

$$V_{cn} = R_c i_c + \frac{d}{dt} (L_{ac} i_a + L_{bc} i_b + L_{cc} i_c + e_c)$$

Assume,

$$R_a = R_b = R_c = R \quad (2)$$

$$L_{aa} = L_{bb} = L_{cc} = L_s \quad (3)$$

$$L_{ab} = L_{ba} = L_{ca} = L_{ac} = L_{bc} = L_{cb} = M \quad (4)$$

In the matrix form,

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s & M & M \\ M & L_s & M \\ M & M & L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (5)$$

Since $i_a + i_b + i_c = 0$ and with $L_s - M = L$

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (6)$$

where

R : Stator resistance per phase, assumed to be equal for all phases

L_s : Stator inductance per phase, assumed to be equal for all phases.

M : Mutual inductance between the phases.

i_a, i_b, i_c : Stator currents/phase.

The instantaneous induced emfs can be written as given in equation

$$e_a = f_a(\theta_r) \lambda_p \omega_m$$

$$e_b = f_b(\theta_r) \lambda_p \omega_m \quad (7)$$

$$e_c = f_c(\theta_r) \lambda_p \omega_m$$

where, ω_m is the rotor mechanical speed and θ_r is the rotor electrical position.

The torque equation is given as

$$T_e = \lambda_p [f_a(\theta_r) i_a + f_b(\theta_r) i_b + f_c(\theta_r) i_c] \quad (8)$$

The equation of motion of system is

$$T_e = J \frac{d\omega}{dt} + B\omega_m + T_l \quad (9)$$

$$J \frac{d\omega_m}{dt} = \frac{1}{J} [T_e - T_l - B \cdot \omega_m] \quad (10)$$

$$\frac{d\theta_r}{dt} = \frac{P}{2} \omega_m \quad (11)$$

where, P is the number of rotor poles. The state variable (θ_r), rotor position, is required to have the function $f_a(\theta_r)$ which is given as the trapezoidal function:

$$\begin{aligned} f_a(\theta_r) &= 1 & 0 < \theta_r < \frac{\pi}{3} \\ f_a(\theta_r) &= \left(\frac{\pi}{2} - \theta_r\right) * \frac{6}{\pi} & \frac{\pi}{3} < \theta_r < \frac{2\pi}{3} \\ f_a(\theta_r) &= -1 & \frac{2\pi}{3} < \theta_r < \pi \\ f_a(\theta_r) &= -1 & \pi < \theta_r < \frac{4\pi}{3} \\ f_a(\theta_r) &= (\theta_r - 3 * \pi/2) * \frac{6}{\pi} & \frac{4\pi}{3} < \theta_r < \frac{5\pi}{3} \\ f_a(\theta_r) &= 1 & \frac{5\pi}{3} < \theta_r < 2\pi \end{aligned}$$

The induced emfs are result of derivatives of flux linkages, which are continuous functions. The phase voltage equations of BLDC motor are identical to armature voltage equation of DC motor.

Closed loop control of Blcdc motor Drive

Figure 1 represents closed loop control of BLDC motor drive. As seen in figure there are two loops, the outer loop is called speed control loop and inner loop is current control loop. The actual speed of the motor is compared with reference value, the error is applied to the speed controller. The speed controller generates reference command value i_{ref}^* which is compared with position of rotor, from which, in turn, reference phase currents are generated. The phase currents are compared with reference currents, difference is applied to hysteresis current controller from which, in turn switching functions are generated for three-phase voltage source inverter (VSI). The BLDC motor is supplied by inverter output voltages V_{an}, V_{bn}, V_{cn} [4].

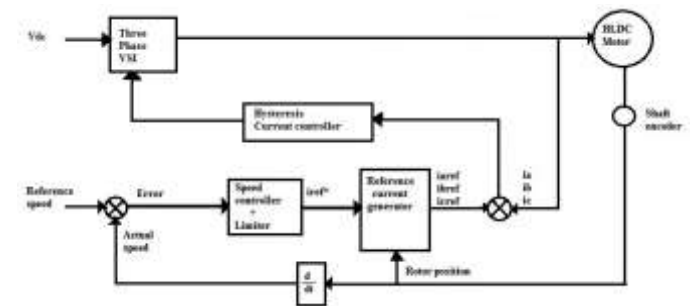


Figure 1. Closed loop control of BLDC drive

Magnitude Optimum Multiple Integration tuning method

A Magnitude optimum multiple integration tuning method is of tuning PID controller furnishes non-oscillatory closed-loop response for a huge class of process models. This method calculate controller parameter from identified model of the process. The tuning procedure for the PID controller is given for those processes which can be approximated by the following transfer function:

$$G_P(s) = K_{pr} \frac{1+b_1s+b_2s^2+\dots+b_ms^m}{1+a_1s+a_2s^2+\dots+a_ns^n} \quad (12)$$

and a_1 to a_n and b_1 to b_m are the corresponding parameters ($m \leq n$) of the process transfer function, where 'n' can be an arbitrary positive integer value. The direct identification of K_{pr}, a_1 to a_n, b_1 to b_m is compound and arduous, to overcome this, MOMI method uses the concept 'moments(areas)' which can be expressed by integrating the process open-loop step response after applying the step-change (dU) at the process input at $t=0$. The graphical representation of moment (area) is shown in figure 4, where y_0 and u_0 represents scaled process output and process input time respectively.

The process transfer function can be expressed as areas by using the following infinite-order expression:

$G_p(s) = A_0 - A_1s + A_2s^2 - A_3s^3$ (13)
where parameters A_i ($i = 0, 1, 2, \dots$) represent time-weighted integrals of the process response. The moments are obtained by calculating unvarying integrals of the process output and input signals during change in the process steady-state. Therefore, in practice the process can be easily parameterised by the moments. The moments A_1 to A_5 can also be calculated directly from the process transfer function after determination of process steady-state gain K_{pr} from process output [6]-[9].

The process steady-state gain is calculated from the process output as

$$K_{pr} = \frac{(y_1 - y_0)}{du} = A_0 \quad (14)$$

and by using K_{pr} , the areas A_1 to A_5 can be calculated as :

$$A_1 = K_{pr}(a_1 - b_1) \quad (15)$$

$$A_2 = K_{pr}(b_2 - a_2) + (A_1 a_1) \quad (16)$$

$$A_3 = K_{pr}(a_3 - b_3) + (A_2 a_1) - (A_1 a_2) \quad (17)$$

$$A_4 = K_{pr}(b_4 - a_4) + (A_3 a_1) - (A_2 a_2) + (A_1 a_3) \quad (18)$$

$$A_5 = K_{pr}(a_5 - b_5) + (A_4 a_1) - (A_3 a_2) + (A_2 a_3) - (A_1 a_4) \quad (19)$$

By using areas A_1 to A_5 , the PID controller parameters can be calculated as :

$$T_d = (A_3 A_4 - A_2 A_5) / (A_3 A_3 - A_1 A_5) \quad (20)$$

$$K_p = A_3 / 2(A_1 A_2 - A_3 K_{pr} - T_d A_1^2) \quad (21)$$

$$T_i = (A_3) / (A_2 - T_d A_1) \quad (22)$$

$$\text{inv} \begin{bmatrix} -A_1 & A_0 & 0 \\ -A_3 & A_2 & -A_1 - A_0 \\ -A_5 & A_4 & -A_3 - A_2 - A_1 - A_0 \end{bmatrix} X \begin{bmatrix} K_i \\ K_p \\ K_d \end{bmatrix} = \begin{bmatrix} 0.5 \\ 0 \\ 0 \end{bmatrix} \quad (23)$$

CASCADE CONTROLLER DESIGN BY MOMI TUNING METHOD

The most popular structures for the process control is cascade control, it can be applied when process can be split into two or more parts [11]. The three parameters of PID controller K_p , K_i , K_d , has to be tuned so that to obtain desired performance from the drive [12]. This type of control can be used for the reduction of current and speed error in motor drives [13]. The design of overall drive system involves

tuning of inner and outer loop PID controllers [14]. The matlab/simulink model of cascaded BLDC drive is shown in figure 2. The overall BLDC drive process $G(s) = G_1(s) G_2(s)$ is split into $G_1(s)$ and $G_2(s)$ as:

The inner loop process (inverter and BLDC motor) transfer function is

$$G_2(s) = \frac{0.02538s + 2.08}{1.55e^{-10}s^3 + 6.378e^{-6}s^2 + 0.006615s + 1} \quad (24)$$

$$G_1(s) = \frac{2.45}{0.012s + 1} \quad (25)$$

From transfer function $a_0=1$, $a_1=0.006615$, $a_2=6.378 \times 10^{-6}$, $a_3=1.55 \times 10^{-10}$, $b_0=2.08$, $b_1=0.02538$.

The outer loop process (load) transfer function is

From transfer function $a_0=1$, $a_1=0.012$, $b_0=2.45$

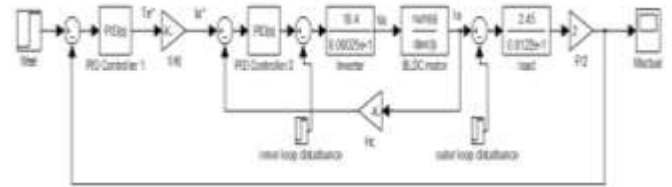


Figure 2. Matlab/simulink model of BLDC motor drive

A. Inner and outer loop controller tuning

The open-loop process input and output of process $G_2(s)$ and $G_1(s)$ is shown in figure 3 and figure 4 respectively, from which steady-state process gain K_{pr} is obtained. With known value of process gain, the areas A_1 to A_5 are calculated using equations (15) – (19). With these areas, PID controller parameters are calculated using equation (23). The calculated areas and controller parameters for the inner loop are presented in table 1.

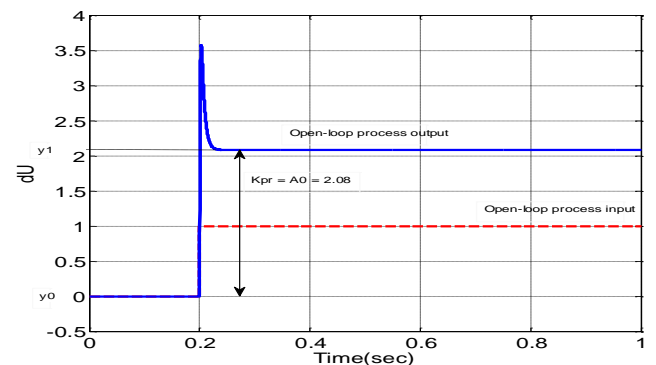


Figure 3. Open-loop process input and output of inner-loop

TABLE 1. CALCULATED AREAS AND CONTROLLER PARAMETERS OF INNER LOOP

Moments(Areas)					
$A_0=K_{Pr}$	A_1	A_2	A_3	A_4	A_5
2.08	-0.039	-2.7×10^{-4}	-1.5×10^{-6}	-8.50×10^{-9}	-4.64×10^{-6}
PID controller parameters					
K_I	K_P	K_D	T_D	T_I	
9.8270	0.0560	0	9.432×10^{-4}	0.0066	

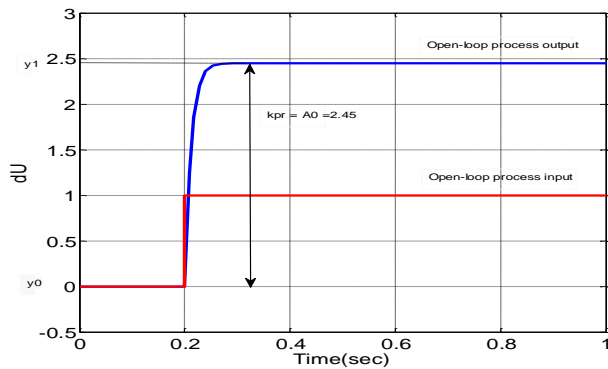


Figure 4. Open-loop process input and output of outer loop

TABLE 2. CALCULATED AREAS AND CONTROLLER PARAMETERS

Moments(Areas)					
$A_0=K_{Pr}$	A_1	A_2	A_3	A_4	A_5
2.45	0.0294	3.52×10^{-4}	4.23×10^{-6}	5.0803×10^{-8}	6.09×10^{-10}
PID controller parameters					
K_I	K_P	K_D	T_D	T_I	
1.1068	0.0133	0	0	0.0120	

Results and Discussion

In the cascade model of BLDC drive given above, the set-speed(reference speed) is taken as $\omega_{ref} = 73.3$ rad/sec.

A. Analysis of motor drive without disturbance:

The speed response of the drive is shown in figure 5(a), it can be seen that speed response is excellent without any oscillations and steady state error. The current error from the inner-loop is shown in figure 5(b). The set-point tracking (reference speed) is shown in figure 5(c), it can be seen that tracking performance is excellent with the proposed control strategy. The speed error from the outer-loop is shown in figure 5(d).

B. Analysis of motor drive with inner loop disturbance :

The speed response is shown in figure 6(a), it can be seen that actual speed recovered to desired speed in very less time under the disturbance in the inner-loop. The response of reference current under disturbance in inner-loop is shown in figure 6(b). The current error under disturbance and the set-point (reference speed) tracking under disturbance in

inner-loop are shown in figures 6(c) and 6(d) respectively.

C. Analysis of motor drive with in outer loop disturbance :

The speed response with the proposed cascade control strategy under the disturbance in the outer-loop is shown in figure 7(a), it can be seen that speed recovered without any overshoot in less time. The reference current change under the disturbance in the outer loop is shown in figure 7(b). The current error of the inner-loop under the disturbance in the outer loop is shown in figure 7(c). The set-point (reference speed) tracking under outer loop disturbance is shown in figure 7(d), it can be seen that performance is good even under the disturbance and sudden changes in the reference speed.

D. Analysis of motor drive with different values of K_p , T_i , T_d :

Dynamic responses of speed under both inner loop and outer loop disturbances and with different values of K_p , T_i , T_d without disturbance in the proposed cascade control system are shown in figure 8(a) – 8(c) respectively. The response with different values of K_p from 0.001 to 0.01 is shown in figure 8(a), it can be seen that with increase in K_p value overshoot increases. The response with different values of T_i from 0.01 to 0.1 is shown in figure 8(b), it can be seen that with increase in T_i rise time and settling time increases. The response with different values of T_d from 0.001 to 0.01 is shown in figure 8(c), it can be seen that oscillations increases with decrease in T_d value.

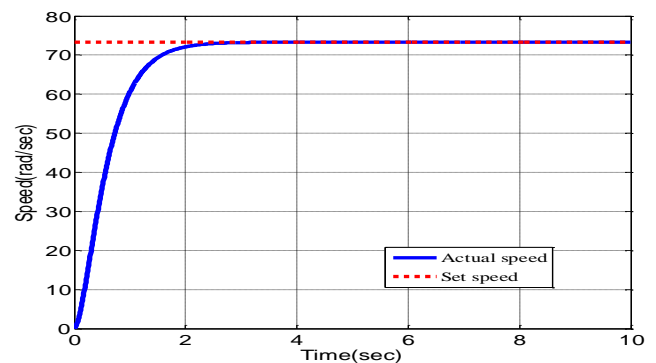


Figure 5(a)

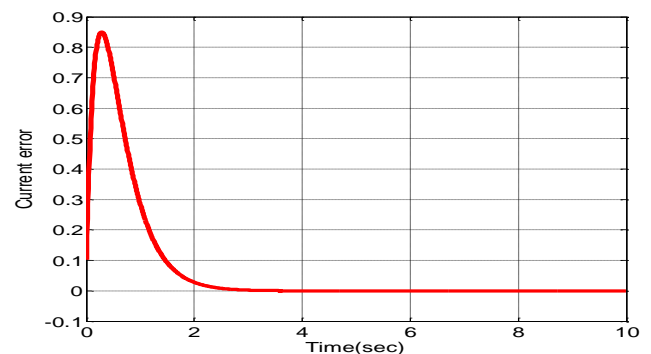


Figure 5(b)

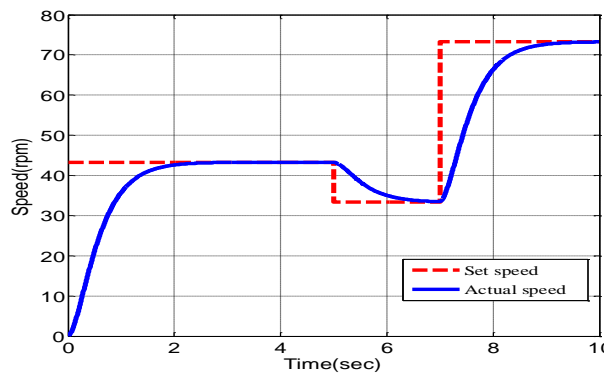


Figure 5(c)

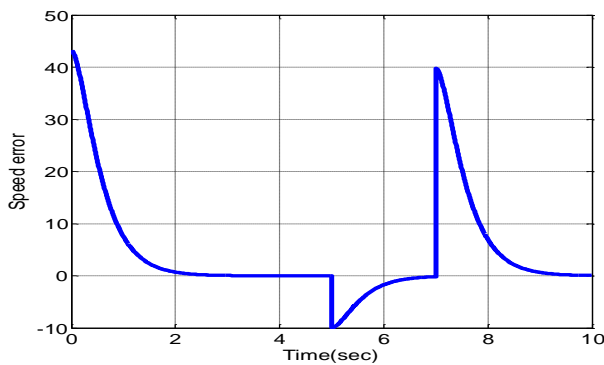


Figure 5(d)

Dynamic responses of speed, current loop error, set-point tracking and speed loop error with the proposed cascade control system are shown in figure 5 (a) – 5(d) respectively.

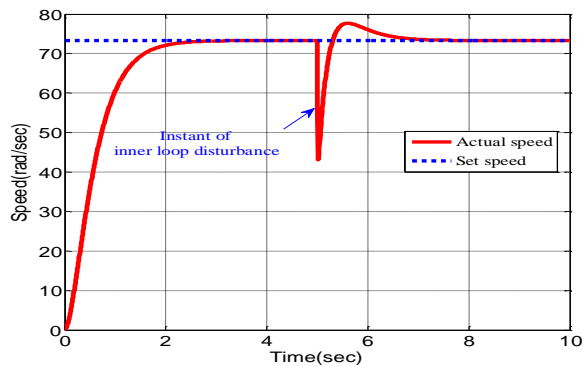


Figure 6(a)

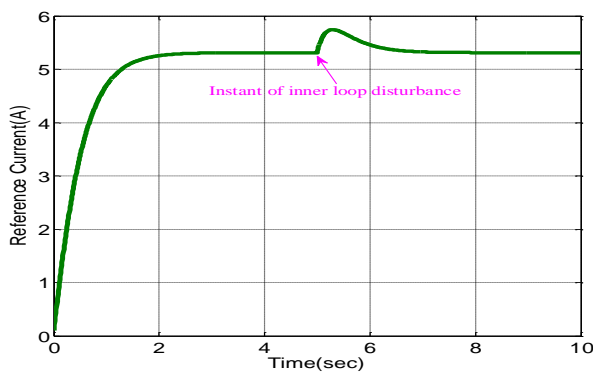


Figure 6(b)

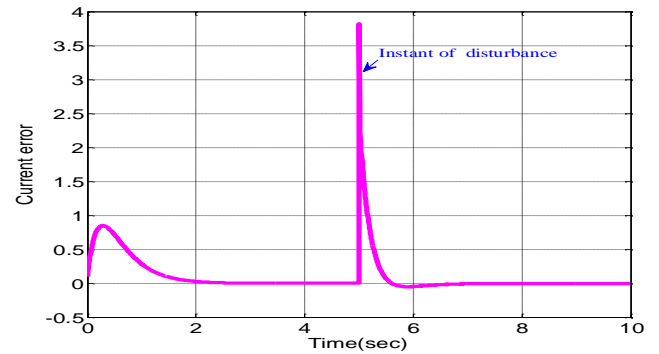


Figure 6(c)

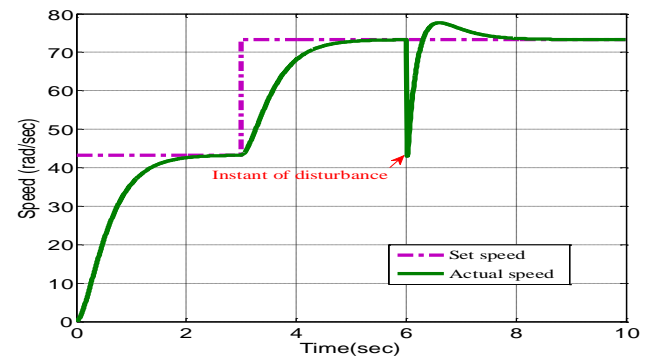


Figure 6(d)

Dynamic responses of speed, reference current command generated, current loop error and set-point tracking under inner loop disturbance with the proposed cascade control system are shown in figures 6(a) – 6(d) respectively.

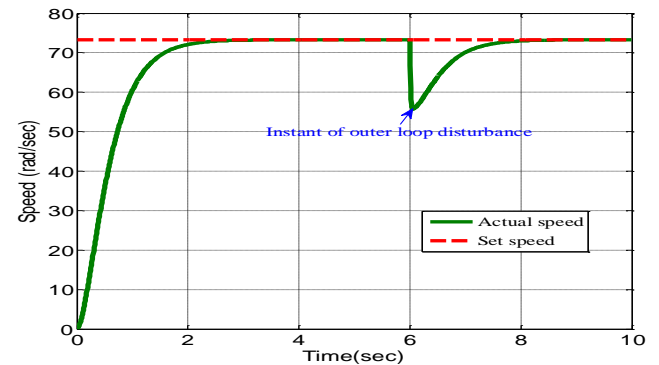


Figure 7(a)

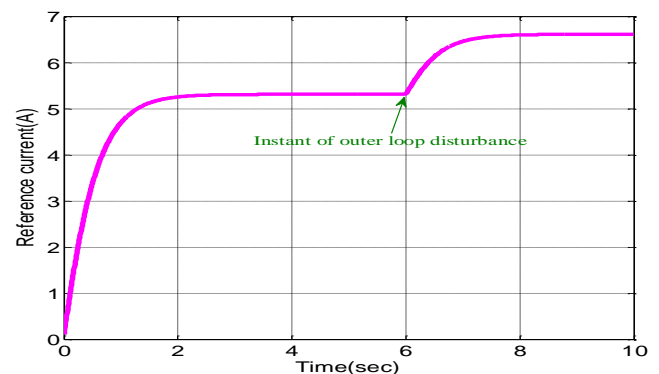


Figure 7(b)

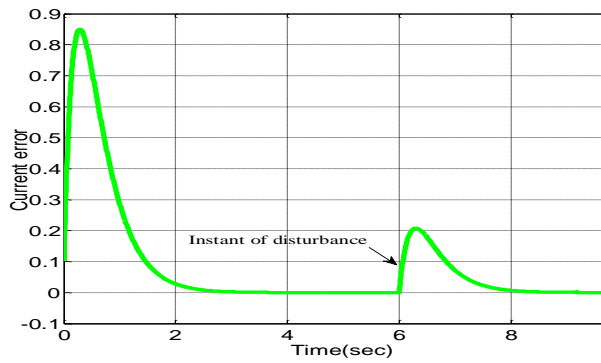


Figure 7(c)

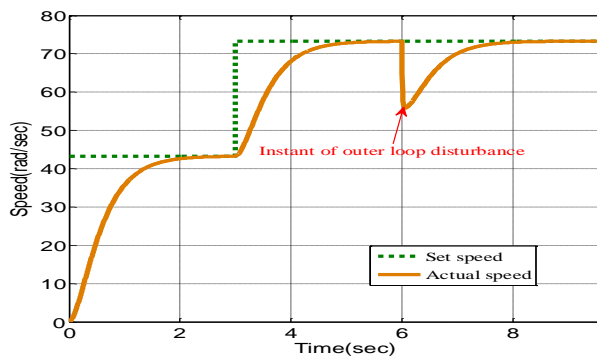


Figure 7(d)

Dynamic responses of speed, reference current command generated, current loop error and set-point tracking under outer loop disturbance with cascade control system are shown in figures 7(a) – 7(d) respectively.

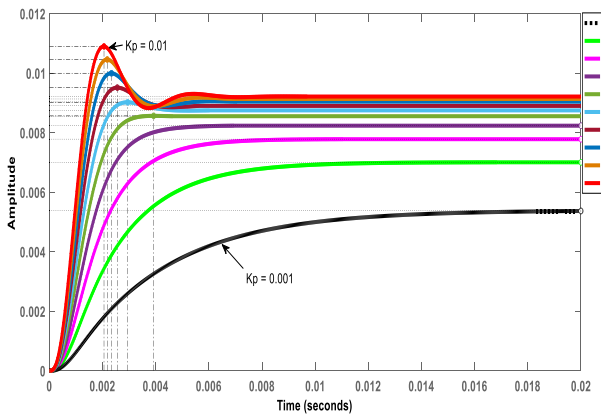


Figure 8(a)

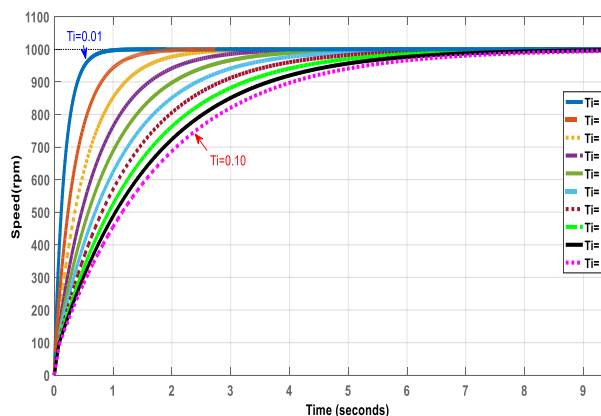


Figure 8(b)

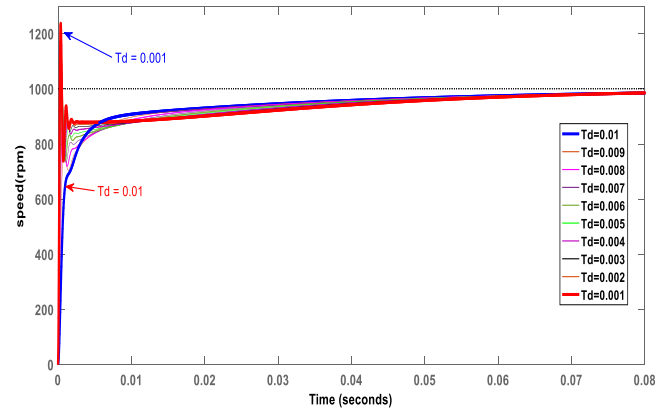


Figure 8(c)

Response with different values of K_p , response with different values of T_i and response with different values of T_d are shown in figures 8(a) – 8(c) respectively.

Conclusion

In this paper, cascaded control of brushless motor drive is proposed with MOMI tuning method to determine the parameters of PID controllers used in inner loop and outer loop. The motor drive system has been simulated using MATLAB/ SIMULINK. Several simulation tests were performed to investigate the robustness of the drive system and simulation results demonstrate the capability of performing under set-point changes, inner loop and outer loop disturbances. The dynamic responses with different values of controller parameters K_p , T_i , and T_d were effective in their control actions. Therefore the proposed cascade control opens a new platform for the control of brushless motor drives.

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