

Modeling and Simulation of Brushless DC Motor with PI Speed Control

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Abstract: Brushless DC motor has many advantages such as simple structure, high torque to weight ratio, high efficiency, etc. Hence, it is widely used in aerospace, robotics and office automation. This study presents the mathematical model of Brushless DC (BLDC) motor and shows the values of various technical parameters by using MATLAB/Simulink and study of speed control of BLDC motor drive with Proportional Integral (PI) control. The simulation is carried out for 120° mode of operation. Finally, a PI controller is applied for closed loop under various load conditions.

Key words: BLDC motor, modeling of BLDC motor, PI-controller, operation, mathematical, aerospace

INTRODUCTION

BLDC motor is defined as a type of self-synchronous rotary motor controlled by electronic commutation unlike DC motors have mechanical commutator. As BLDC motor neither has mechanical commutator nor slip rings, so, it has great advantages more than conventional DC motor and induction motor such as better speed-torque characteristics, high efficiency, high dynamic response and wide speed ranges (Yedamale, 2009). The Proportion Integral (PI) controller is used for amplify the speed error and adjust gate pulse signal to control the six switches of the three phase bridge.

Mathematical model of the BLDC motor: Typically, the mathematical model of a brushless DC motor is not totally different from the conventional DC motor. The major difference is the phases involved in the operation of BLDC motor drive will peculiarly affect the resistive and the inductive nature of the BLDC Model arrangement (Pillay and Krishnan, 1989). The equivalent circuit of BLDC motors shown in Fig. 1 and 2. The dynamic equations of BLDC motor can be expressed in this matrix form:

$$\begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad (1)$$

The electromagnetic torque developed by the motor is given by:

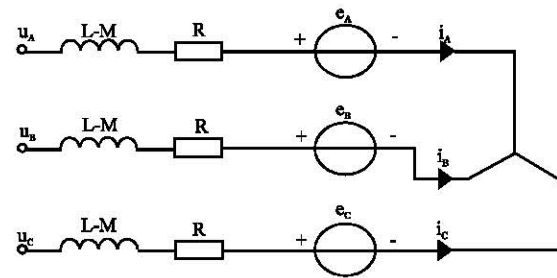


Fig. 1: Equivalent circuit of BLDC motor

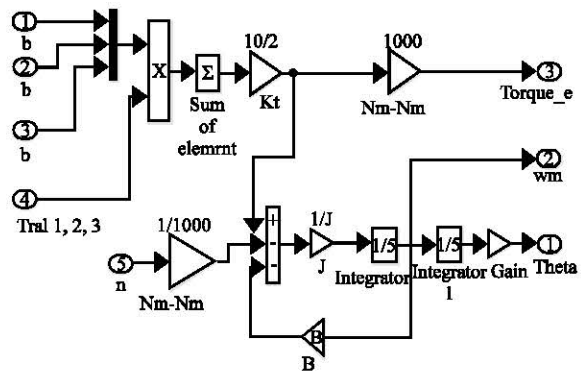


Fig. 2: Structure diagram of BLDC motor with load torque

$$T_e = \frac{e_A i_A + e_B i_B + e_C i_C}{\Omega} \quad (2)$$

The motion equation has to be included as:

$$T_e - T_L = J \frac{d\Omega}{dt} + B_v \Omega \quad (3)$$

The transfer function of BLDC motor is expressed by:

$$G_u(S) = \frac{\Omega(s)}{U_d(s)} = \frac{K_T}{L_a JS^2 + (r_a J + L_a B_v)S + (r_a B_v + K_e K_t)} \quad (4)$$

$$G_L(S) = \frac{\Omega(s)}{U_L(s)} = \frac{r_a + L_a S}{L_a JS^2 + (r_a J + L_a B_v)S + (r_a B_v + K_e K_t)} \quad (5)$$

Where:

$$K_e = 2P\psi_m = 4PNsB_m$$

$$K_m = 2P\psi_m$$

MATERIALS AND METHODS

MATLAB/Simulink Models: Figure 3 shows the BLDC motor model and describing the blocks using for it (Agrawal *et al.*, 2014; Mitra and Ojha, 2015). The commutation block consists of subsystem which including three phase inverter model as shown in Fig. 4. The BLDC motor block consists of three subsystem back EMF equation, state equation and mechanical equation as shown in Fig. 2. Speed generator block is mechanical part of BLDC motor. By using this model the actual speed (ω) of BLDC motor can be obtained by using the mechanical

and electrical equation. The speed generator block is shown in Fig. 5. Current generator block to obtain the stator phase current (i_{A_s} , i_{B_s} , i_{C_s}) by using state equation as shown in Fig. 6 and 7. Back EMF generator block is used to create Back EMF of BLDC motor as shown in Fig. 8 (Tomer and Dubey, 2016; Makavana *et al.*, 2013).

Controllers

PI speed controller: The actual speed of BLDC motor is obtained by using the speed position encoder. The actual speed of the motor compared with reference speed and the resulting error is estimated as:

$$\Omega_e = \Omega_d - \Omega_a \quad (6)$$

The resulting error is given to PI controller. The transfer function of of PI controller is estimated as:

$$G_s(S) = K_p \left(\frac{1+S}{T_i S} \right) \quad (7)$$

The PI speed controller as shown in figure is used as the input of reference current block.

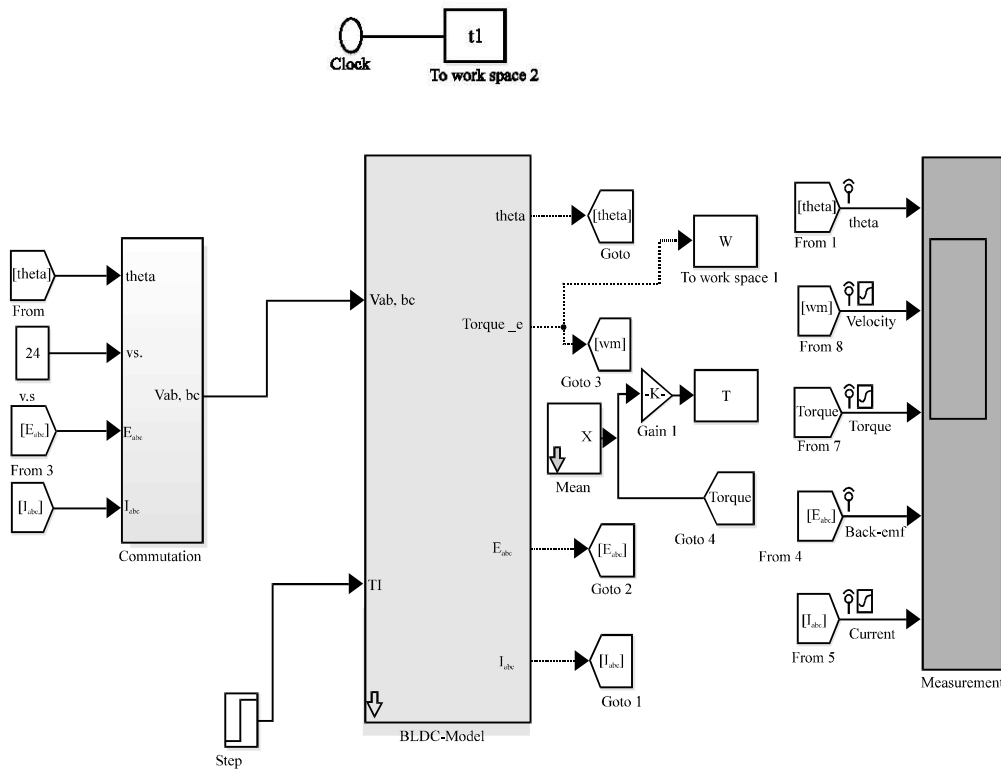


Fig. 3: BLDC motor Simulink Model

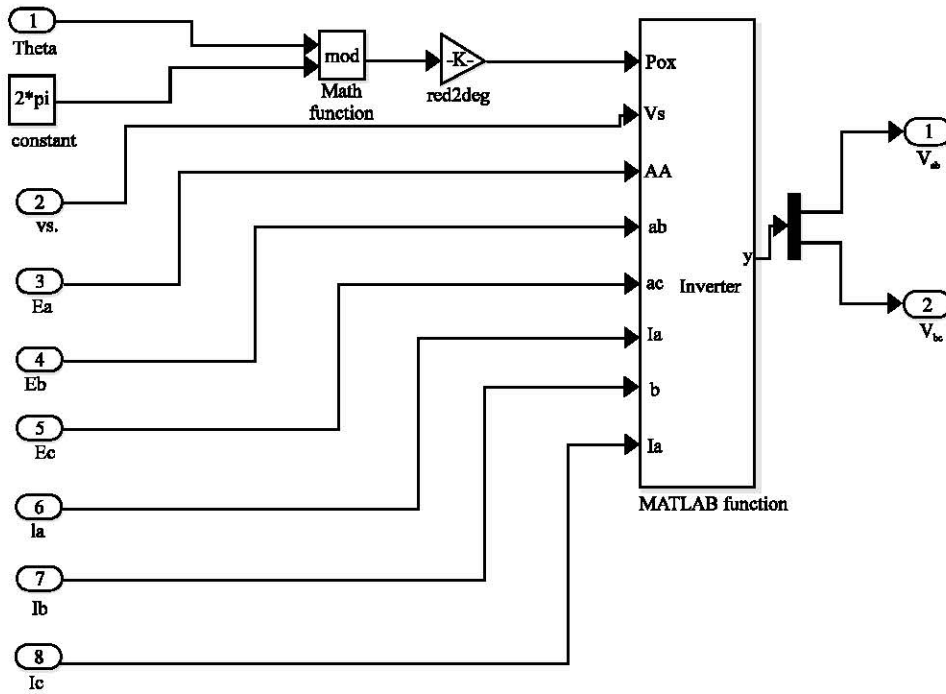


Fig. 4: Three phase inverter model

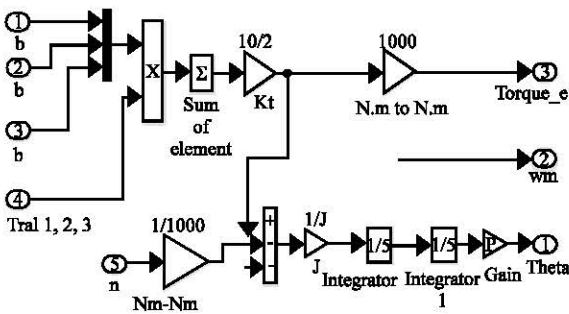


Fig. 5: Speed generator model

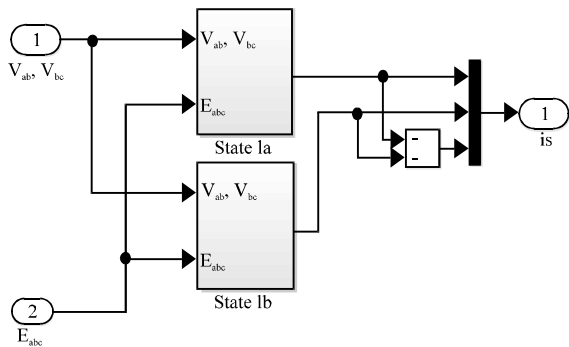


Fig. 6: Current generator model

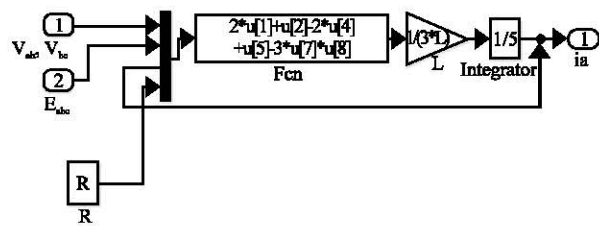


Fig. 7: State equation model

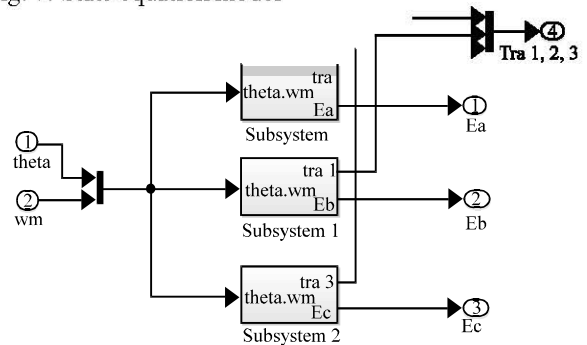


Fig. 8: Back EMF generator model

RESULTS AND DISCUSSION

The simulation results includes the different parameter of BLDC motor such as motor speed, electromagnetic torque, stator phase current, phase back EMF with respect (Fig. 9 and 10).

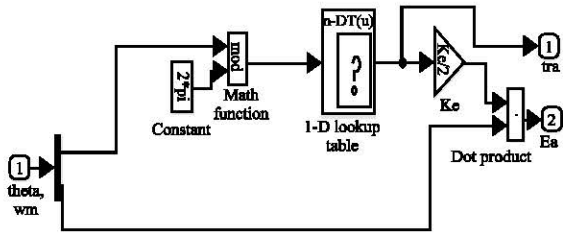


Fig. 9: Back EMF subsystem

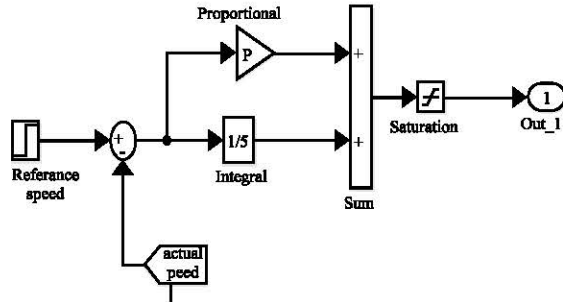


Fig. 10: PI speed controller sub block

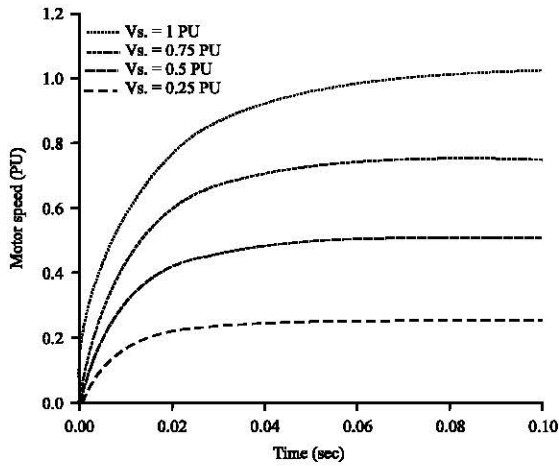


Fig. 11: Relation between PU speed and time (sec) at different motor voltages

Motor performance-time curves at load torque ($TL = 0$)

Motor performance-time curves at different armature voltages: For different armature voltages, the motor speed, the stator phase current and developed torque are calculated for interval time from 0-0.1 sec there are shown in Fig. 11-14.

Figure 11-4 show the motor speed, stator phase current, developed torque and phase back EMF respectively as function of time with motor voltage (V_s) as a parameter.

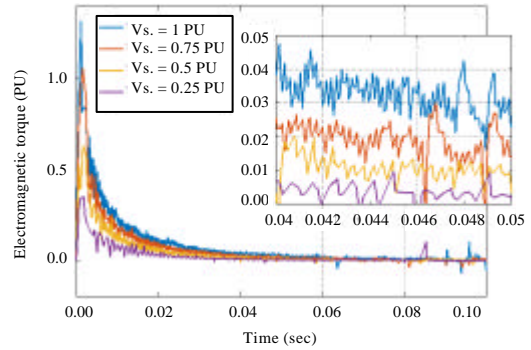


Fig. 12: Relation between PU electromagnetic torque and time (sec) at different motor voltages

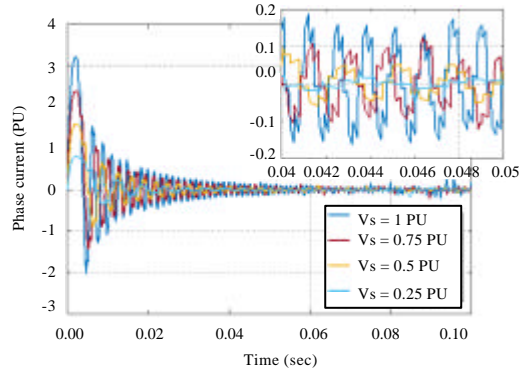


Fig. 13: Relation between PU phase current and time (sec) at different motor voltages

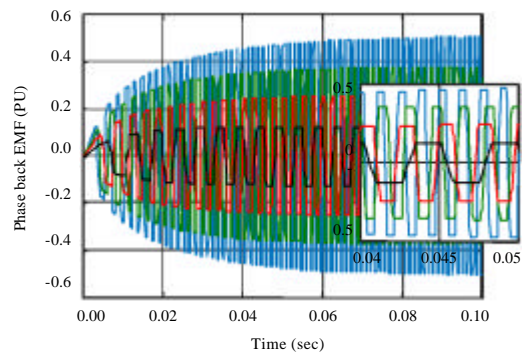


Fig. 14: Relation between PU phase back EMF and time (sec) at different motor voltages

The effect of motor voltage on the motor performance is clear when the motor voltage increases the speed of the motor, phase current, developed torque and phase back EMF are increased.

The current is seen to be oscillating with time according to the chopping frequency and voltage pulse width (Fig. 15-26).

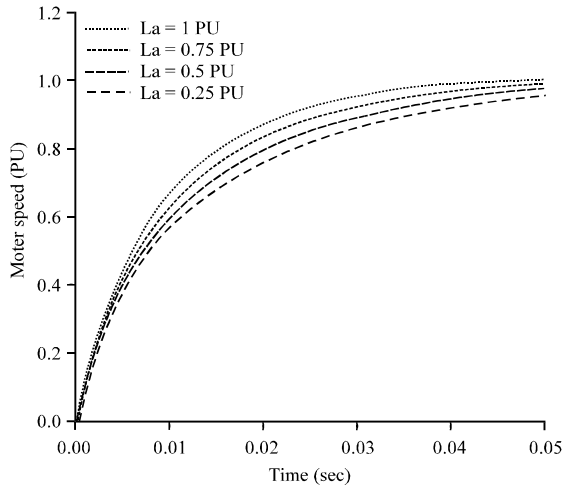


Fig. 15: Relation between PU speed and time (sec) at different armature inductances

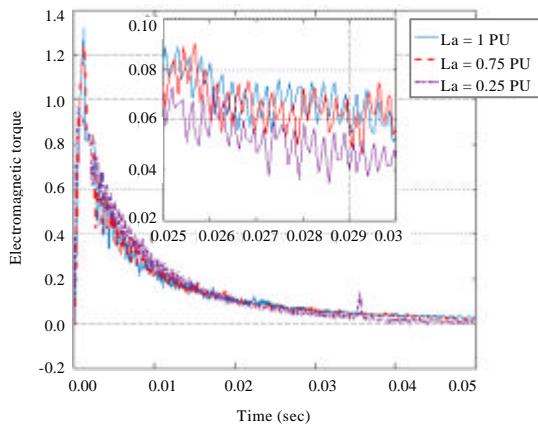


Fig. 16: Relation between PU electromagnetic torque and time (sec) at different armature inductances

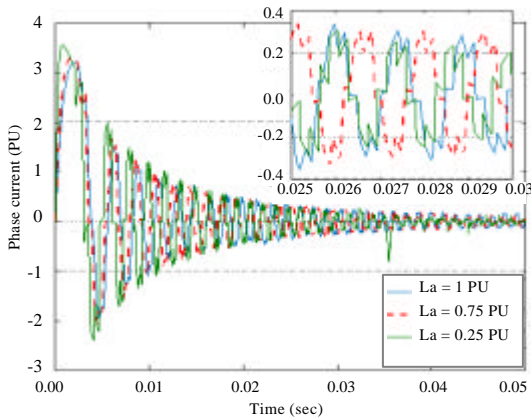


Fig. 17: Relation between PU phase current and time (sec) at different armature inductances

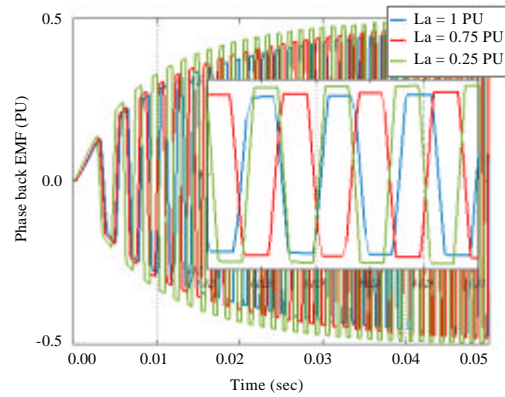


Fig. 18: Relation between PU phase back EMF and time (sec) at different armature inductances

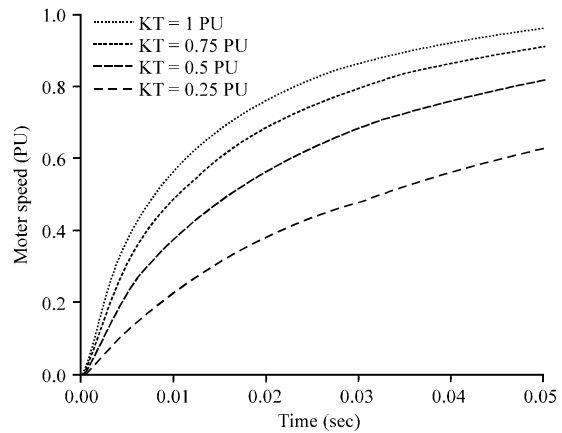


Fig. 19: Relation between PU speed and time (sec) at different torque coefficient

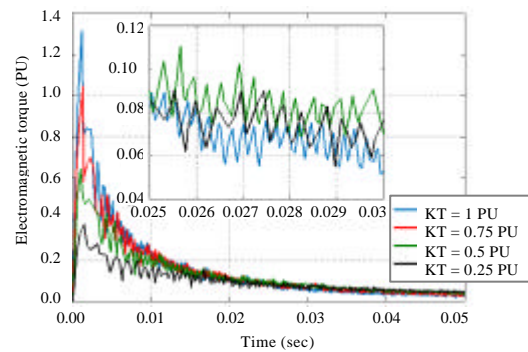


Fig. 20: Relation between PU electromagnetic torque and time (sec) at different torque coefficient

Motor performance-time curves at different armature inductance: The effect of stator inductance on the motor performance is clear when the stator inductance decreases the speed of the motor, phase back EMF are increased, phase current, developed torque are decreased.

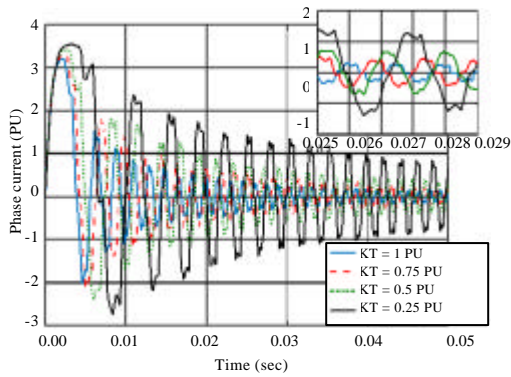


Fig. 21: Relation between PU phase current and time (sec) at different torque coefficient

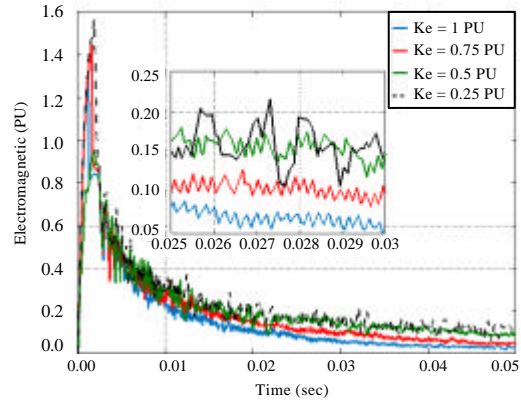


Fig. 24: Relation between PU electromagnetic torque and time (sec) at different back EMF coefficient

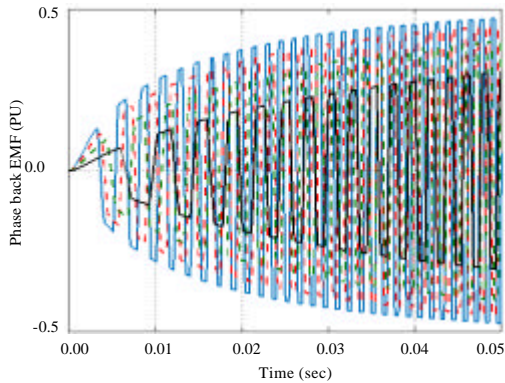


Fig. 22: Relation between PU phase back EMF and time (sec) at different torque coefficient

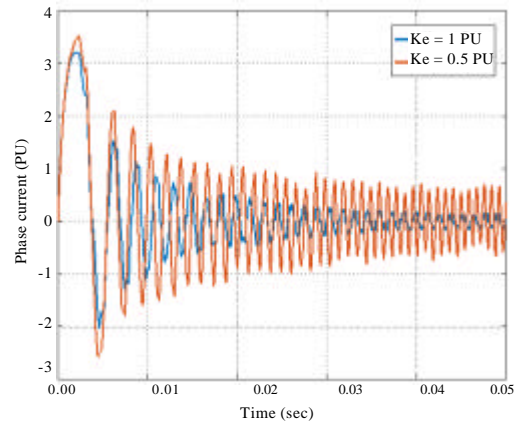


Fig. 25: Relation between PU phase current and time (sec) at different back EMF coefficient

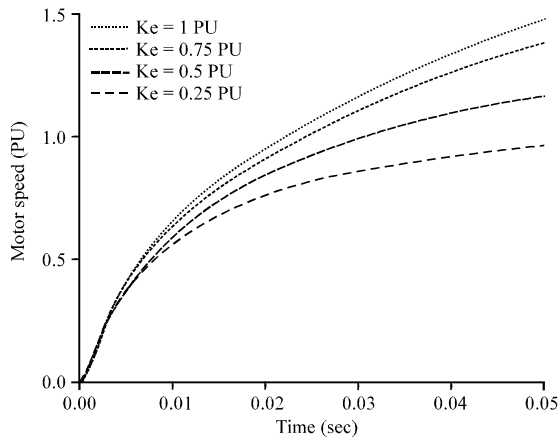


Fig. 23: Relation between PU speed and time (sec) at different back EMF coefficient

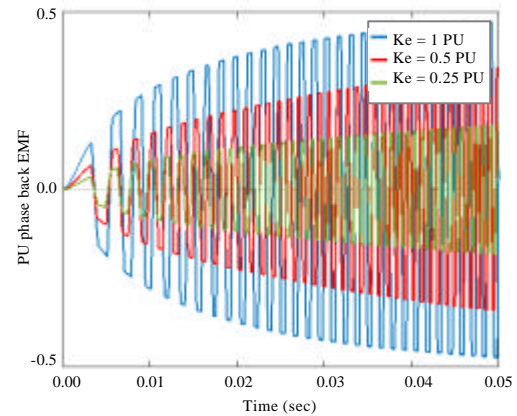


Fig. 26: Relation between PU phase back EMF and time (sec) at different back EMF coefficient

Motor performance-time curves at different torque coefficient: The effect of torque coefficient on the motor performance is clear when the torque coefficient increases the speed of the motor, developed torque and phase back EMF are decreased but phase stator current increased.

Motor performance-time curves at different back EMF coefficient: The effect of back EMF coefficient on the motor performance is clear when the back EMF coefficient

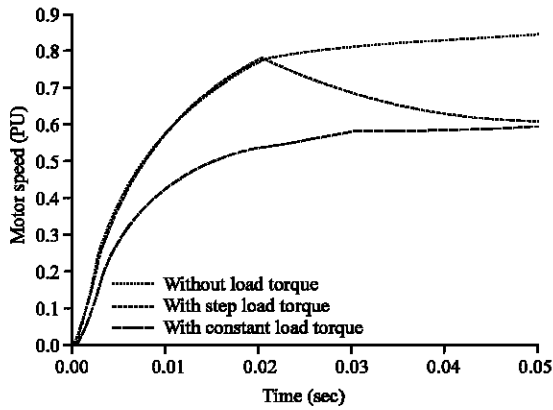


Fig. 27: Relation between PU speed and time (sec) at different load torque condition

increases the speed of the motor, developed torque and stator current are decreased but phase back EMF is increased:

Motor performance-time curves at load torque (TL = constant) and (TL = step load)

All results below of MATLAB program are used to obtain the main operating parameters, namely, the motor speed (n), the stator phase current (i_a) and developed torque (T_d) as function of time during constant load torque ($T_l = 6 \text{ Nm} = 0.3 \text{ PU}$) and step load torque at constant other operating parameters such as ($V_a, R_a, L_a, T_a, J, \dots$).

The dynamic simulation results of the BLDC motor with step load are shown in Fig. 27-30.

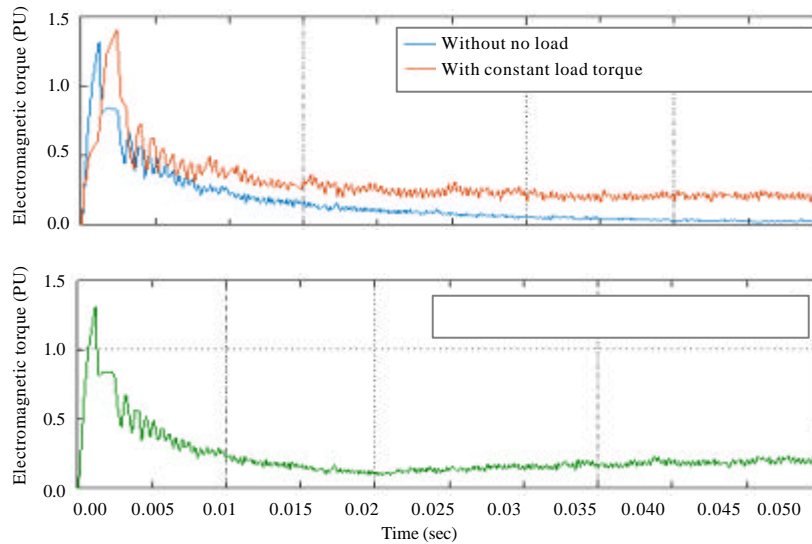


Fig. 28: Relation between PU electromagnetic torque and time (sec) at different load torque condition

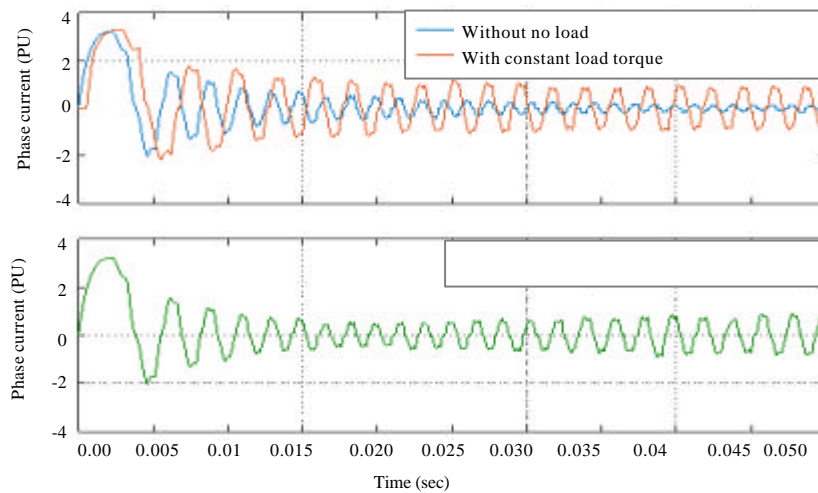


Fig. 29: Relation between PU phase current and time (sec) at different load torque condition

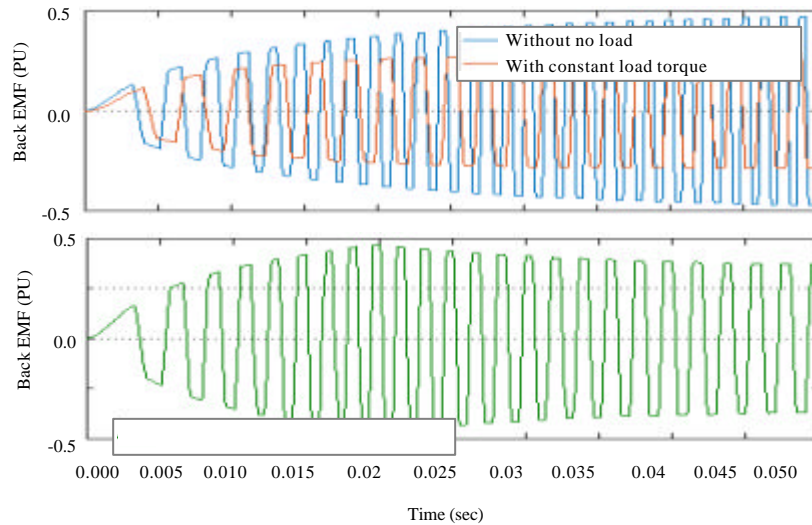


Fig. 30: Relation between p.u phase back EMF and time (sec) at different back EMF coefficient

In Fig. 27-30, the motor starts with no load and then accelerates freely to the steady state. Note that when the load increases suddenly (i.e., jumps from 0-6 Nm at 0.025 sec), the motor speed will decrease with the cycle of the phase voltage and phase current becoming longer. The increase in the current will lead to an increase of the torque, so as to balance the increased load torque. In addition, the amplitudes of the current and torque ripple are also increased. When the load decreases suddenly (i.e., varies from 6-4 Nm at 0.045 sec), the motor speed will increase with the cycle of the voltage and current becoming shorter. Moreover, the amplitude and the ripple of the current and the torque will become smaller. The speed is high enough at 0.025 sec, i.e., the back-EMF is large enough. So, the current cannot quickly respond to the sudden increase of the load with constant bus voltage. Hence, the change of speed is relatively slow. In this condition, the boost circuits can be used to increase the voltage, so as to accelerate the response speed of the current. Similarly, when the load decreases suddenly, we can use the PWM control method to reduce the voltage of the armature winding.

CONCLUSION

This study is propose to evaluate the mathematical model of BLDC motor and the performance of PI controller for speed control of BLDC motor drive system.

NOMENCLATURES

- u_A, u_B, u_C = Phase voltage (V)
- i_A, i_B, i_C = Phase current (A)
- e_A, e_B, e_C = Phase back EMF (V)
- R = Phase resistance (ohm)
- L = Self inductance (H)
- M = Mutual inductance (H)
- T_e = Electromagnetic torque (Nm)
- T_L = Load torque (Nm)

- B = Damping constant (Nsec/m)
- J = Moment of inertia (kgm²)
- K_e = Coefficient of line back-EMF
- K_T = The torque coefficient
- K_i = Integral gain
- K_p = Proportional gain
- T_i = Integral time constant

Greek symbols

- Ω = Angular velocity (rad/sec)
- Ω_r = Reference angular velocity (rad/sec)

Abbreviations

- PI = Proportion Integral controller
- BLDC = Brushless DC Motor
- FLC = Fuzzy Logic Control

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