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Modeling of Brushless DC Motor for Electric Vehicle Application

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Abstract:-*Electric Vehicle has received more attention as an alternative option to traditional vehicles powered by internal combustion engines running on fossil fuels. Automobile industries are targeting sustainable transportation in future. Electric motor plays an important role in electric vehicle. AC motors, DC motors, Reluctance motors are mostly used in automotive application. But BLDC motor is most suitable because of high reliability, high power density, high efficiency, low cost, lower weight and low maintenance requirements due to absence of brushes. In-wheel technology is new concept in which each wheel of EV is driven by separate motor instead of using central drive system. This paper presents developed model of Brushless DC Motor by using MATLAB/Simulink and performance characteristics of motor are observed during various loading conditions. Simulation results obtained from developed model are discussed which gives correct performance of model however it makes brushless dc motor more effective in automotive applications.*
Keywords:-*Brushless DC Motor (BLDC), Proportional Integral Controller (PIC), Electric Vehicle (EV), MATLAB/Simulink*

Nomenclature-

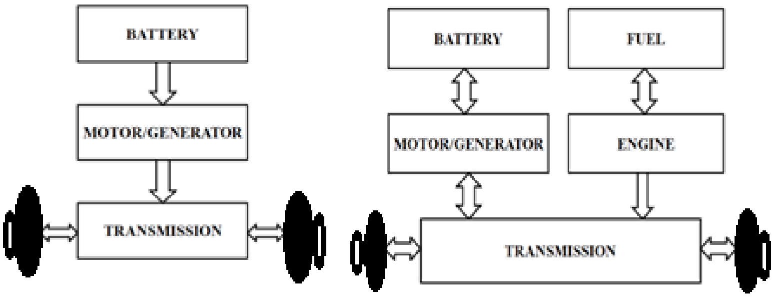
V_{ab}, V_{bc}, V_{ca} =Phase to phase Voltage (Volt)
i_a, i_b, i_c =Phase current (Ampere)
e_a, e_b, e_c =Phase Back-EMF
T_e =Electromagnetic torque (N-m)
T_L =Load/Mechanical torque (N-m)
θ_e =Electrical angle (Degree or ˚)
θ_m =Mechanical angle (Degree or ˚)
J =Rotor inertia (Kg/m²)
ω_m =Rotor speed (rpm)
B =Damping ratio (N-ms)

I. Introduction

A Brushless DC Motor conserves the characteristics of dc motor but eliminates the brushes and commutator hence known as Brushless DC (BLDC) Motor. DC conventional motors can be replaced by brushless dc motor in many cases. Current commutation is done by solid switches said to be electronic commutation but motor is driven by dc voltage source. BLDC motors are available in many different power ratings, from large motors used in electric vehicle to very small motors used in hard drives. Three phase motors are common but in many applications two phase motors are also found [01].

Nowadays, electric vehicles are considered as the future for a sustainable automobile industry as they have several benefits over internal combustion engine vehicles. Electric vehicle consist Motor, Controller and Battery. Electric motor plays significant role in electric vehicle. A wide variety of electric motors have been used for integration in electric vehicles [02-03]. In previous years, DC electric motors were the most probably used, but recent advancements in technology have made AC electric motors much more suitable [04] – AC electric motors are characterized by more power density, less need of maintenance, higher efficiency and greater reliability.

BLDC motor is normally powered by conventional three phase inverter which is controlled by the rotor position information obtained from Hall sensors or simply from hall position sensors [05-07]. In three phase windings use one Hall Sensor for each winding to provide three overlapping signals giving a 60° or 120° wide position range. Whenever the magnetic poles pass near the sensors a high or low signals will produce for indicating North or South Pole. The controller has low cost and desirable stability. It can better perceive energy regenerative braking when the vehicle is decelerating and flux weakening control during high speed [08].



(a) Electric Vehicle (b) Hybrid Vehicle

Fig.1: Block diagram of electric vehicle and hybrid vehicle structure

Due to electronic commutation BLDC Motor have more complex control algorithm as compare to other motors. Hence, for precise and complete control scheme of BLDC accurate model of motor is required. It is necessary to have motor model which gives precise value of torque related to Current and back-EMF. In-wheel technology is using a separate motor mounted inside each wheel instead of one central drive train propelling two or all wheels in conventional electric vehicles. It helps to increase controllability of vehicle and reduces chassis weight. BLDC motor has been used in various applications like aerospace, automotive, industrial automation, instrumentation, medical applications etc. As the brushes are eliminated less maintenance is required by motor also reduces noise susceptibility and sparking. BLDC motor is more advantageous as compared to brushed DC motor and induction motor in electric vehicle application because of its electronic commutation technique and permanent magnet rotor [09].

This paper presents mathematical modeling and analysis of Brushless DC motor for the application of Electric Vehicle. The structure of this paper is organized as section-II deals with construction, operating principle and control of BLDC motor. Section- III describes basic mathematical analysis of BLDC motor. Section –IV deals with Simulink model of 3-phase BLDC motor. Simulation results and conclusion with future scope are described in Section- V and VI.

II. Construction And Operating Principle

A. Brushless DC Motor (BLDC)

BLDC motor is one of the types of synchronous motor which means that magnetic field generated by rotor rotation and magnetic field generated by stator is at the same frequency. Normally slip is seen in induction motor but BLDC motor does not experience slip. However, for control of rotor rotations BLDC motor requires complex electronics structure. As shown in fig. 2, in a BLDC motor, stator with laminated steel core having fixed armature winding and permanent magnets are mounted on rotor. The information of rotor position is obtained from either Hall Effect sensors or coil effect measurements [10].

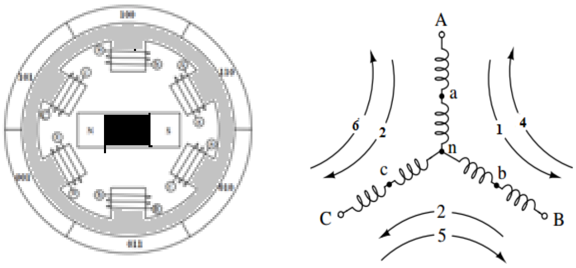


Fig.2: Y-connected BLDC motor construction

B. BLDC Motor Control

BLDC motor can be control by using inverter or electronic commutator, and the commutation is done by controlling the order of conduction on the inverter bridge arm. Fig. 3 shows equivalent block diagram of

BLDC motor with typical H-bridge inverter, Shaft position sensing unit and trigger circuit. DC power supply is given to the motor. Hall Effect sensors are used for predicting the position of rotor [10].

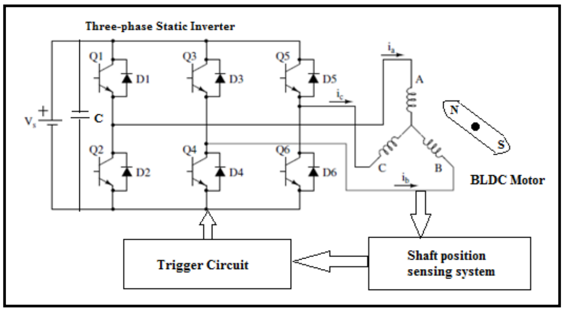


Fig.3: Equivalent Block Diagram of BLDC motor

III. Mathematical Analysis

A three-phase star connected BLDC motor can be described by following electrical and mechanical equations:

$$V_{ab} = R(i_a - i_b) + L\frac{di}{dt}(i_a - i_b) + e_a - e_b \qquad (1)$$

$$V_{bc} = R(i_b - i_c) + L\frac{di}{dt}(i_b - i_c) + e_b - e_c \qquad (2)$$

$$V_{ca} = R(i_c - i_a) + L\frac{di}{dt}(i_c - i_a) + e_c - e_a \qquad (3)$$

$$T_e = k_f \omega_m + J\frac{d\omega_m}{dt} + T_L \qquad (4)$$

Where the symbols V, i and e represents phase to phase voltage (Volt), phase current (Amp) and phase back-EMF of phase a, b and c respectively. R and L are per phase values of resistance (Ω) and inductance (H) respectively. T_e is electrical torque (N-m), T_L is load torque (N-m), J is rotor inertia (Kg/m²), k_f is friction constant, ω_m is rotor speed (rpm)

The back-EMF and electrical torque can be given as,

$$e_a = \frac{k_e}{2}\omega_m F(\theta_e) \qquad (5)$$

$$e_b = \frac{k_e}{2}\omega_m F(\theta_e - \frac{2\pi}{3}) \qquad (6)$$

$$e_c = \frac{k_e}{2}\omega_m F(\theta_e - \frac{4\pi}{3}) \qquad (7)$$

$$T_e = \frac{k_t}{2}[F(\theta_e)i_a + F(\theta_e - \frac{2\pi}{3})i_b + F(\theta_e - \frac{4\pi}{3})i_c \qquad (8)$$

Where, k_e is back-emf constant, k_t is torque constant.

The electrical angle θ_e is equal to the rotor angle times the pole pairs $(\theta_e = \frac{p}{2}\theta_m)$. The function $F(.)$ gives trapezoidal waveform of back-emf. One period of this function can be written as,

$$F(\theta_e) = \begin{cases} 1, & 0 \le \theta_e \le \pi \\ 1 - \frac{6}{\pi}(\theta_e - \frac{2\pi}{3}), & \frac{2\pi}{3} \le \theta_e \le \pi \\ -1, & \pi \le \theta_e \le \frac{5\pi}{3} \\ -1 + \frac{6}{\pi}(\theta_e - \frac{5\pi}{3}), & \frac{5\pi}{3} \le \theta_e \le 2\pi \end{cases} \qquad (9)$$

Equation (1)-(4) are converted to state-space form for convenient use in MATLAB/Simulink. Each voltage equation is in linear combination of other two voltage equations only two voltages are needed. By throwing away one equation and eliminating one equation by using current relationship.

$$i_a + i_b + i_c = 0$$

The voltage equations become

$$V_{ab} = R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_a - e_b \qquad (10)$$

$$V_{bc} = R(i_a + 2i_b) + L\frac{d}{dt}(i_a + 2i_b) + e_a - e_b \qquad (11)$$

And the complete model is given as,

$$\begin{pmatrix} \dot{i_a} \\ \dot{i_b} \\ \dot{\omega_m} \\ \dot{\theta_m} \end{pmatrix} = \begin{pmatrix} \frac{-R}{L} & 0 & 0 & 0 \\ 0 & \frac{-R}{L} & 0 & 0 \\ 0 & 0 & \frac{-kf}{J} & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ \omega_m \\ \theta_m \end{pmatrix} + \begin{pmatrix} \frac{2}{3}L & \frac{1}{3}L & 0 \\ \frac{-1}{3}L & \frac{1}{3}L & 0 \\ 0 & 0 & \frac{1}{J} \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} V_{ab} - e_{ab} \\ V_{bc} - e_{bc} \\ T_e - T_L \end{pmatrix} \qquad (12)$$

$$\begin{pmatrix} i_a \\ i_b \\ i_c \\ \omega_m \\ \theta_m \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ \omega_m \\ \theta_m \end{pmatrix} \qquad (13)$$

For improvement and simplification of computational efficiency, machine models are often transformed to rotating reference frame [01].Model will get more complex after implementation of final state space equations (12) and (13). Even though neutral point of motor is not attainable but practically it is possible to approximate it with zero crossing point of back-EMF. State space to Laplace transform and vice versa can also be written for zero initial condition systems. Hence final state space equation is divided into two separate and easy mechanical as well as electrical Laplace equations applied by phase to neutral voltages with the help of this BLDC model will become more simple and convenient for implementation of various control techniques. According to electrical rotation of rotor in each phase separately ideal reference back-EMF signal of motor is also produced and applied as negative feedback to phase voltage [09].

IV. Simulation of BLDC Motor

The designed model of Brushless DC motor is simulated in MATLAB/Simulink having specifications given in Table-I. The machine parameter are Phase resistance *Rs*= 1.43 ohm, Phase inductance L_s =9.4 m-H, J = 1.5e-3 kg/m², B = 2e-3 N-ms, Back-emf flat area=120˚, Flux=0.2158 wb, No. of poles=P=4 these parameters are used in given modeling of BLDC Motor with no-load torque and 15 Nm load torque conditions.

Table I: Specification of BLDC Motor

Description	**Value**	**Unit**
Voltage	220	Volt AC
Rated Frequency	50	Hz
Rated Speed	1500	rpm
Poles	4	-

As shown in fig.4 three-phase, 4 poles trapezoidal back-emf BLDC motor is fed with balanced supply of 220V, 50Hz. Trapezoidal back-emf is referring that mutual inductance between rotor and stator has trapezoidal shape [11]. Due to trapezoidal back-emf abc phase variable model is more applicable than d-q axis. System includes BLDC motor subsystem block which shown in Fig.5 consists of current, back-EMF and speed calculation blocks. Measurement block is connected to give output parameters. Hall Effect signals for the movement of rotor are produced according to electrical degree.

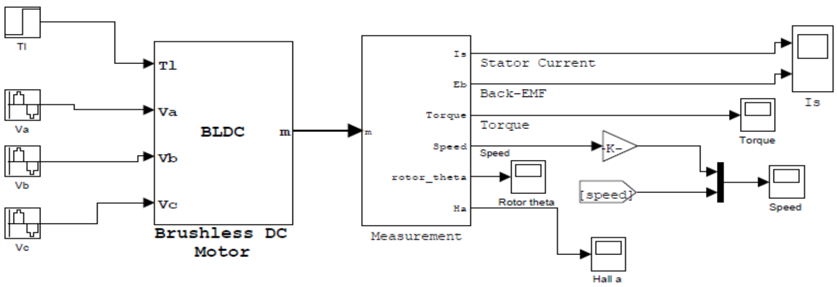


Fig.4: Simulink model of Three-phase Brushless DC Motor

Fig.5 shows detail Simulink model of 3-phase BLDC motor. Voltage, Current and torque equation equations are used to implement the model of motor. Current block shows the calculation of current through phase-abc as well as electromagnetic torque, Back-EMF block gives calculation of back-EMF of all phases and electromagnetic speed (ω_e). Speed calculation block calculates speed of rotor with the input of load torque (T_L) and electromagnetic torque (Te) where Hall Effect block gives signal for the movement of rotor that is in electrical degrees which will be either by 60˚ or 120˚.

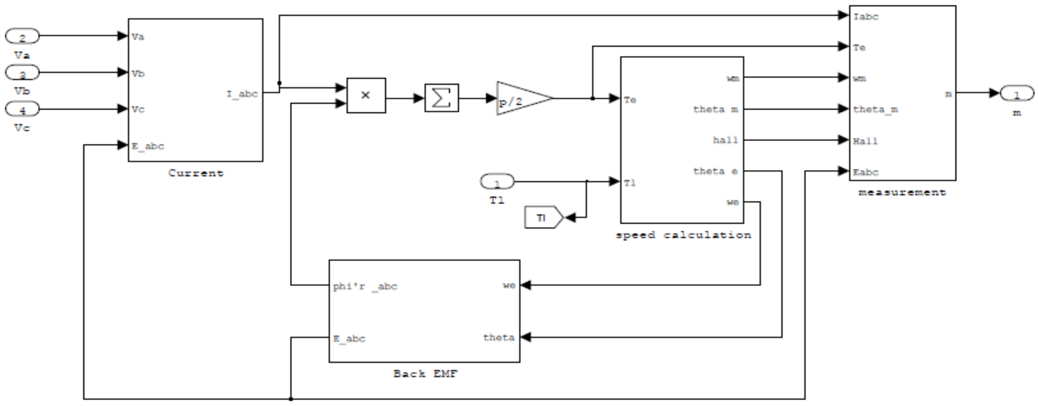


Fig.5: Simulink model of Three-phase Brushless DC Motor

V. Simulation Results

The developed MATLAB model of 3-phase BLDC motor gives following results in terms of current, voltage, torque and speed etc. Fig. 6 shows the stator current and back-EMF for phase A at no-load condition with respect to time and fig. 7 shows torque with respect to time at no-load condition. Fig.8 shows speed of BLDC motor with respect to time is 1501 rpm. Rotor theta angle during no-load is 156.5˚ at time=1second shown in fig.9 and fig.10 gives hall effect signal for phase A.

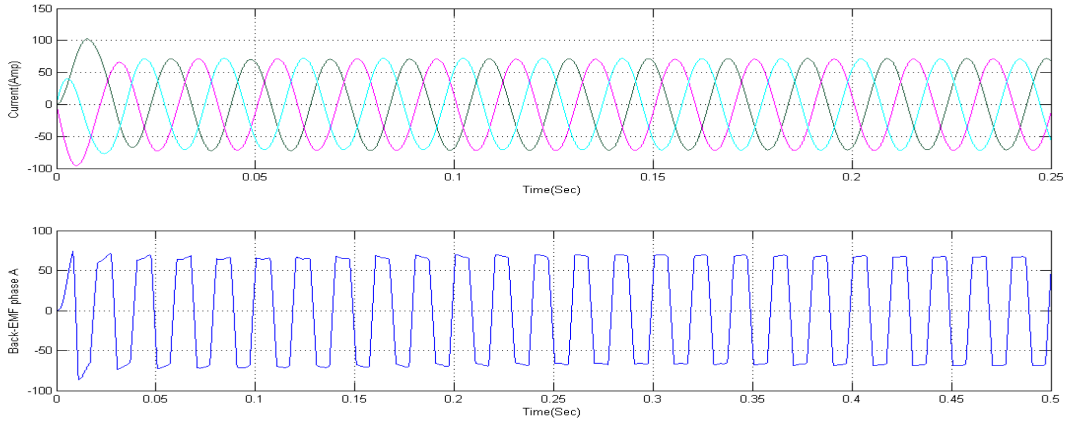


Fig.6: Stator current and Back-EMF of phase A at no-load

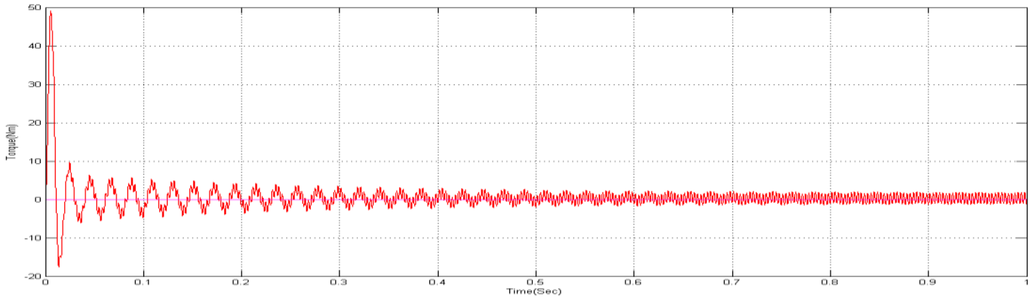


Fig.7: Torque of BLDC Motor at no-load

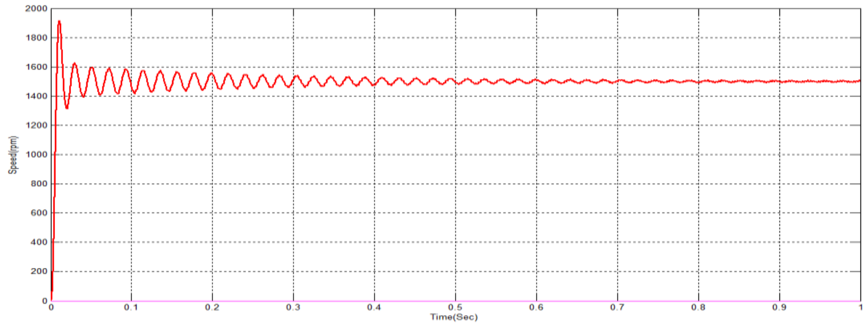


Fig.8: Speed of BLDC Motor at no-load

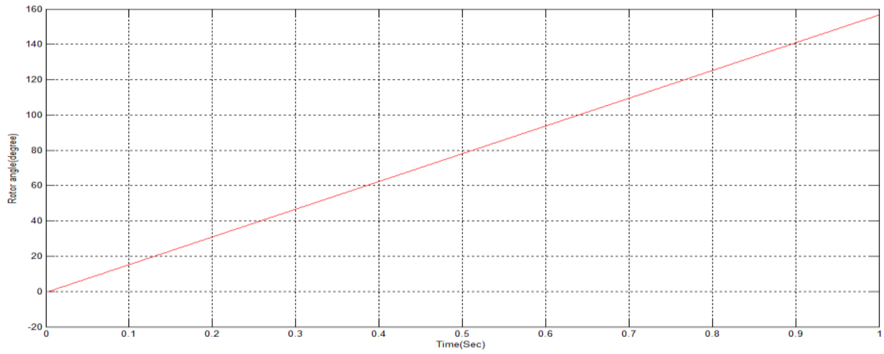


Fig 9: Rotor theta of BLDC Motor at no-load

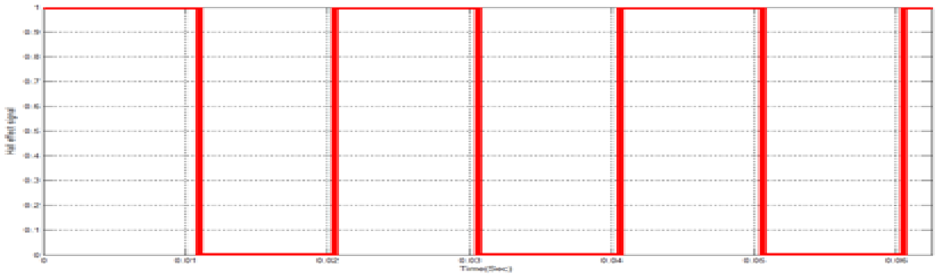


Fig.10: Hall Effect signal for phase A at no-load condition

Model is also simulated for loading condition that is when T_L=15N-m fig.11 shows stator current and back-EMF for phase A under load-condition with respect to time. Fig.12 shows torque 14.72 N-m when load torque is 15N-m. Fig.13 gives speed is 1528rpm. Fig.14 shows rotor theta angle is 156.3˚ at t=1Second. Hall Effect signal for phase A is given in fig.15.

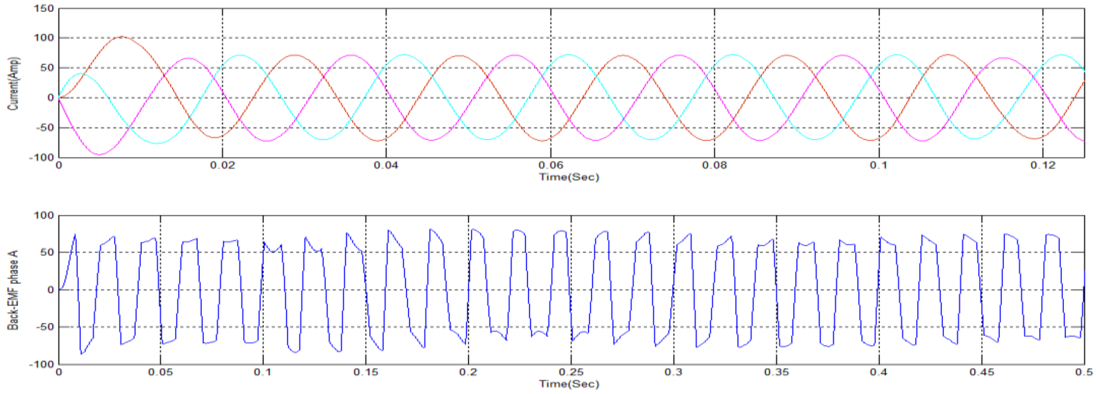


Fig.11: Stator current and Back-EMF for phase A at 15Nm load condition

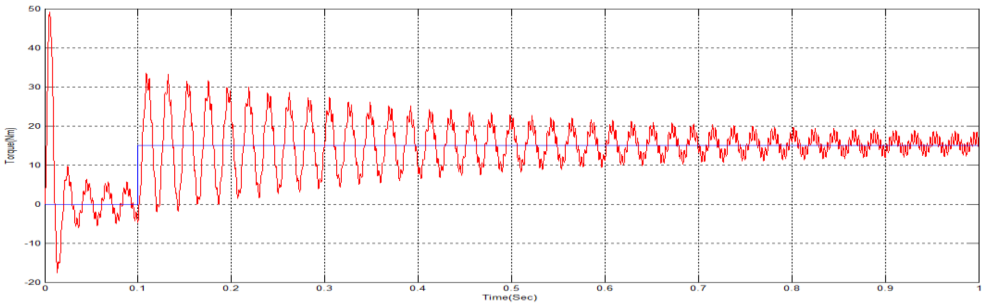


Fig.12: Torque of BLDC Motor at 15Nm load condition

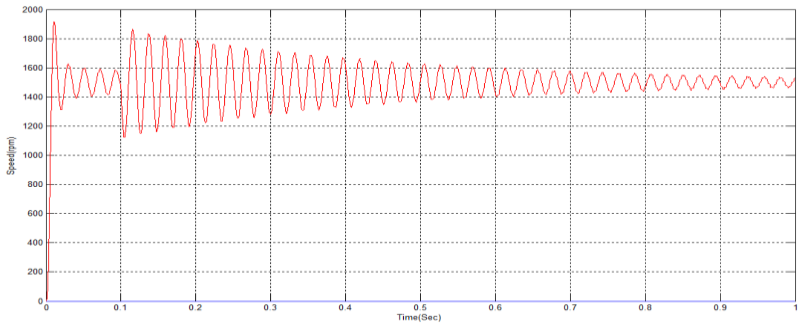


Fig.13: Speed of BLDC motor at 15Nm load condition

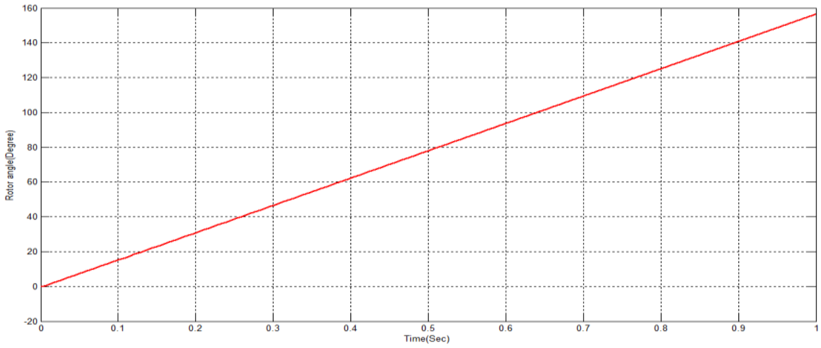


Fig.14: Rotor theta angle of BLDC motor at 15Nm load condition

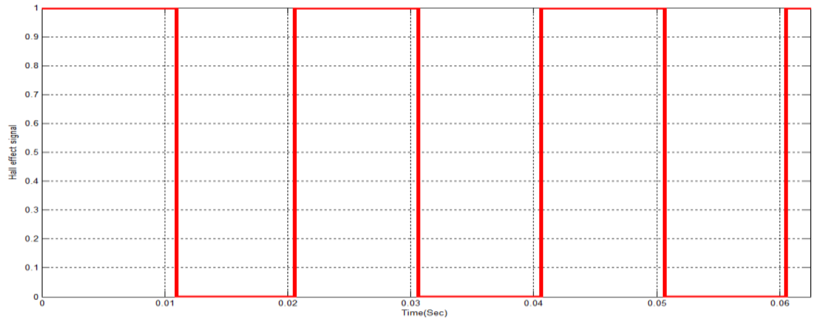


Fig.15: Hall effect signal for phase A at 15 Nm load condition

VI. Conclusion

Due to green house gases emission and reduced energy consumption sustainable transportation is a need of future all over the world. Electrical and Hybrid vehicles are the good solution for solving global warming issues commonly created by internal combustion engine vehicles. Motor is use to drive the wheels in EV.

This paper presents an investigation of the performance of a three-phase motor fed from a three-phase balanced power supply. A mathematical model similar to those representing conventional machines has been adopted to reflect the motor operation. This paper proposes working principle, mathematical analysis and control of 3-phase BLDC motor by using abc-axis property. The results indicate smooth operation of motor at synchronous speed.

The developed model of 3-phase BLDC motor with trapezoidal back-EMF is simulated in MATLAB/Simulink. Simulation results under no-load and for load condition are showing proper performance of model. Output characteristics and simplicity of model make it effectively useful in design of BLDC motor drives with different control algorithms for various applications. A BLDC motor has higher power density, higher efficiency and higher speed range. Therefore it is a good choice for automotive industries. In future renewable energy such as solar, wind etc can also be useful for charging battery and driving vehicle.

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