Simulation Model and Sensorless Control of Permanent Magnet Brushless DC Motor Based on Speed Independent Position Function

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ABSTRACT

The permanent magnet brushless dc (BLDC) motor is increasingly being used in computer, aerospace, military, automotive, industrial and household products because of its high torque, compactness, and high efficiency. The BLDC motor is inherently electronically controlled and requires rotor position information for proper commutations of current. However, the problems of the cost and reliability of rotor position sensors have motivated research in the area of position sensor less BLDC motor drives. This paper presents a novel sensor less position detection technique with a new physical concept based on a speed-independent position function for the BLDC motors. Since the shape of the position function is identical at all speeds, it provides a precise commutation pulse at steady state as well as transient state. The proposed method does not rely on the measured back-EMF; hence the need for external hardware circuitry for sensing terminal voltages has been removed. This paper presents the theory and implementation of a novel sensor less control technique for the brushless dc (BLDC) motor. The proposed new sensor less drive method solves the problem of the sensor less BLDC motor drives at very low speeds. It provides a highly accurate and robust sensor less operation from near zero to high speeds. For this purpose, an approach, a new flux linkage function is defined, that is speed-independent. The validity of the proposed method is verified through simulation. An equation based model for Open Loop and Closed Loop Operation of PMBLDC Drive operation is done in Matlab/Simulink. Equation based Matlab/Simulink simulation results show the proposed controller has the advantages of fast response and less steady-state error when compared to that of the conventional PI controller.

Key Words: BLDC Motor, Sensorless, Back emf, Speed

INTRODUCTION:

Brushless dc motors use an electronic control to sequentially energize the stator poles. The motor consists of permanent magnet rotor and the distributed stator windings are wound such that electromotive force is trapezoidal. Permanent magnet motors are usually small because of permanent magnet rotor. Brushless dc motors provide less maintenance, longer life, lower EMI and quieter operation than wound rotor DC motor due to elimination of brushes. They have better speed torque characteristics and low inertia, which improves their dynamic performance when compared to a dc motor.

The permanent magnet machines have the feature of high torque to size ratio. They possess very good dynamic characteristics due to low inertia in the permanent magnet rotor. Permanent magnet machines can be classified into dc commutator motor, permanent magnet synchronous motor (PMSM) and permanent magnet brushless dc (PMBLDC) motor. The permanent magnet dc commutator motor is similar in construction to the conventional dc motor except that the field winding is replaced by permanent magnets[1]. The PMSM and PMBLDC motors have similar construction with polyphase stator windings and permanent magnet rotors, the difference being the method of control and the distribution of windings. The PMSM motor has sinusoidally distributed stator windings and the controller tracks sinusoidal reference currents. The PMBLDC motor is fed with rectangular voltages and the windings are distributed so as to produce trapezoidal back emf. In order to rotate the PMBLDC motor the stator windings have to be energized in a proper sequence. The sequence for clockwise rotation is exactly opposite of counter clockwise rotation. The sequence of excitation is determined by the rotor position. The rotor position is sensed by Hall effect sensors embedded in stator [2].

1. CONTROL PRINCIPLE:

Most popular and practical sensorless drive methods for BLDC motors rely on speed-dependent back emf. Since the back emf is zero or undetectably small at standstill and low speeds, it is not possible to use the back emf sensing method in the low speed ranges. Also, the estimated commutation points that are shifted by 30° from zero crossing of back emf have position error in transient state. The flux estimation method also has significant estimation error at low speed, in which the voltage equation is integrated in a relatively large period of time. To overcome the above drawbacks, a novel method, based on a new speed-independent function, is proposed, one that is based on a new physical insight.

The general voltage equation of one of the active phases is given by

$$v_x = Ri_x + \sum_{k=1}^{n} \frac{d\psi_{kx}(\theta, i_x)}{dt} \tag{1}$$

where v_x is the active phase voltage, R is the phase resistance, i_x is the phase current, θ is the rotor position, $\psi_{kx}(\theta, i_x)$ is the total flux linkage of the active phase, and "n" is the number of phases. The flux linkage in the active phase includes both self and mutual flux linkages. For three-phase BLDC motors, the total flux linkage of the phase A is

$$\psi_A = L_{aa}(\theta,i_a).i_a + L_{ab}(\theta,i_b).i_b + L_{ac}(\theta,i_c).i_c + \lambda_{ar}(\theta) \tag{2}$$

Where, the first term, $L_{aa}(\theta, i_a).i_a$, represents the self flux linkage of phase A, the second and third term stand for the mutual flux linkage with phases B and C; and the fourth term, $\lambda_{ar}(\theta)$ stands for the flux linkage due to the permanent magnet that is attached on the rotor. The first three terms of eq.2 are function of current and position, and the $\lambda_{ar}(\theta)$ is the function of position. Therefore, the flux profile has a close relationship with the dynamic performances. Since the BLDC motor uses permanent magnets, the permeability of the attached permanent magnet is considered as that of air, and hence, typically, the motor has small inductance variation[3]. Therefore, if the motor is operated within the rated current, the saturation effect of inductance due to current level is usually neglected. For the surface-mounted permanent magnet (SMPM) type of BLDC motors, the permanent magnets are roundly attached on the round surface of the rotor, and hence, the inductance variation by rotor position is negligibly small. Based on the characteristics of the SMPM type of BLDC motors, the flux profile can be simplified as eq.3 along with the following assumptions:

- The motor is operated within the rated condition and hence the saturation effect due to current level is neglected.
- The leakage inductance is negligibly small and hence neglected.
- Iron losses are negligible.

$$\psi_A = L_{aa} \,.\, i_a + L_{ab} \,.\, i_b + L_{ac} \,.\, i_c + \lambda_{ar}(\theta) \tag{3}$$

Substituting eq.3 into eq.1 gives

$$v_a = R_a i_a + \frac{d}{dt}\left(L_{aa} i_a + L_{ab} i_b + L_{ac} i_c\right) + \frac{d\lambda_{ar}(\theta)}{dt} \tag{4}$$

In balanced three-phase BLDC motors

$$L_{aa} = L_{bb} = L_{cc} = L_s$$
$$L_{ba} = L_{ab} = L_{ca} = L_{ac} = L_{bc} = L_{cb} = M \tag{5}$$

Where, L_s, and M represent the self-inductance and mutual-inductance, respectively. Substituting eq.5 into eq.4 gives

$$v_a = R_a i_a + \frac{d}{dt}\left(L_{aa} i_a + M i_b + M i_c\right) + \frac{d\lambda_{ar}(\theta)}{dt} \tag{6}$$

For a balanced star connected BLDC motors,

$$i_a + i_b + i_c = 0 \tag{7}$$

Using eq.7, the eq.6 is simplified as

$$v_a = R_a i_a + L\frac{di_a}{dt} + \frac{d\lambda_{ar}(\theta)}{dt} \quad (L = L_s - M) \tag{8}$$

where L represents the phase inductance under balanced conditions. The last term in the voltage equations is so called back EMF, and the term is redefined as

$$v_a = R_a i_a + L\frac{di_a}{dt} + \frac{d\left(k_e f_{ar}(\theta)\right)}{dt} \tag{9}$$

$$v_a = R_a i_a + L\frac{di_a}{dt} + k_e \cdot \frac{d\theta}{dt} \cdot \frac{d\left(f_{ar}(\theta)\right)}{d\theta} \tag{10}$$

where k_e stands for the back emf constant. It is seen that $\lambda_{ar}(\theta)$ in eq.8 is expressed as a constant value times a flux linkage function that is changed only by the rotor position as shown in eq.9. The $f_{ar}(\theta)$ is a flux linkage form function that is a function of rotor position. Since some manufacturers do not provide a motor neutral point, the line-to-line voltage equations are used as follows:

$$V_{ab} = R(i_a - i_b) + L\frac{d(i_a - i_b)}{dt} + k_e \cdot \omega \cdot \frac{d\{f_{ar}(\theta) - f_{br}(\theta)\}}{d\theta} \tag{11}$$

$$V_{ab} = R(i_a - i_b) + L\frac{d(i_a - i_b)}{dt} + k_e \cdot \omega \cdot \frac{df_{abr}(\theta)}{d\theta} \tag{12}$$

where ω stands for the instantaneous speed. The $f_{abr}(\theta)$ is a line-to-line flux linkage form function that is a function of the rotor position. Now we define a new function, $H(\theta)_{ab}$, as

$$H(\theta)_{ab} = \frac{df_{abr}(\theta)}{d\theta} \tag{13}$$

Then, $H(\theta)_{ab}$ can be derived as

$$H(\theta)_{ab} = \frac{1}{\omega \cdot k_e}\left[(V_a - V_b) - R(i_a - i_b) - L\left(\frac{di_a}{dt} - \frac{di_b}{dt}\right)\right] \tag{14}$$

Since the $H(\theta)_{ab}$ function itself has a one to one relationship with rotor position, it is possible to use this function for position estimation. But as shown in eq.14, to know the $H(\theta)_{ab}$ function, the instantaneous speed term, that is unknown for dynamic operations, is required to calculate the function.

To eliminate the instantaneous speed term, ω that causes trouble in using the $H(\theta)_{ab}$ function for position estimation, one line- to-line $H(\theta)$ function is divided by another line-to- line $H(\theta)$ function, and the divided new speed independent function is named $G(\theta)$. For example

$$G(\theta)_{bc/ab} = \frac{H(\theta)_{bc}}{H(\theta)_{ab}} = \frac{\left[(V_b - V_c) - R(i_b - i_c) - L\left(\frac{di_b}{dt} - \frac{di_c}{dt}\right)\right]}{\left[(V_a - V_b) - R(i_a - i_b) - L\left(\frac{di_a}{dt} - \frac{di_b}{dt}\right)\right]} \tag{15}$$

2. COMMUTATION PROCESS:

Fig. 1 shows the $G(\theta)$ functions $G(\theta)_{bc/ab}$, $G(\theta)_{ab/ca}$, and $G(\theta)_{ca/bc}$, waveform based on eq.15. The standard commutation instant is when the $G(\theta)$ functions are changed from positive infinity to negative infinity as in Fig.1. After careful investigation of the shape of $G(\theta)$ function, to provide the best indirect position-function that is speed-independent with high sensitivity at each commutation point, the ratio of two line-to-line $H(\theta)$ functions is sequentially utilized[4][5].

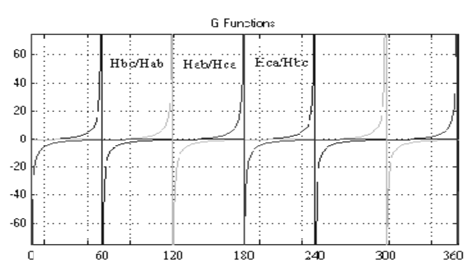

Fig. 1 G function waveforms

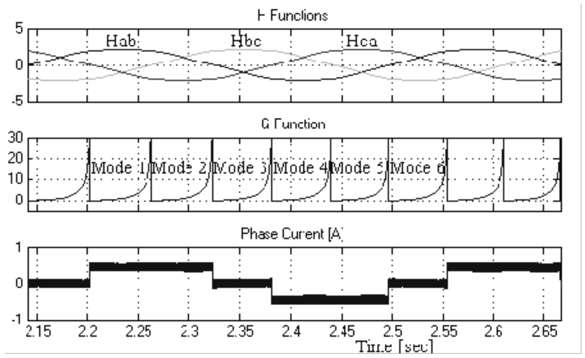

Fig. 2 H function, G function, Phase Current using proposed sensorless method

Two line-to-line $H(\theta)$ functions are used in each mode as Table 1. As shown in Fig.2, at mode 1, $G(\theta)_1$ is used as a position estimation equation; after a 60° electrical angle, at mode 2, $G(\theta)_2$ is utilized. The time duration of each mode in Fig.2 corresponds to 60° by electrical angles.

Table 1 G Function modes

Mode 1 and 4	$G(\theta)_1 = \dfrac{H(\theta)_{ca}}{H(\theta)_{bc}} = \dfrac{V_{ca} - Ri_{ca} - L\dfrac{di_{ca}}{dt}}{V_{bc} - Ri_{bc} - L\dfrac{di_{bc}}{dt}}$
Mode 2 and 5	$G(\theta)_2 = \dfrac{H(\theta)_{bc}}{H(\theta)_{ab}} = \dfrac{V_{bc} - Ri_{bc} - L\dfrac{di_{bc}}{dt}}{V_{ab} - Ri_{ab} - L\dfrac{di_{ab}}{dt}}$
Mode 3 and 6	$G(\theta)_3 = \dfrac{H(\theta)_{ab}}{H(\theta)_{ca}} = \dfrac{V_{ab} - Ri_{ab} - L\dfrac{di_{ab}}{dt}}{V_{ca} - Ri_{ca} - L\dfrac{di_{ca}}{dt}}$

When the $G(\theta)$ function reaches a predefined threshold value, the motor is commutated. The threshold value is defined based on the current rising time and desired advanced angle. From the sequential combination of the $H(\theta)$ functions as shown in Table 1, the $G(\theta)$ function can be made as shown in Fig.2. It is noted that the commutation signal can be generated at the peak point that is the most sensitive part of the $G(\theta)$ function. From the available stator current and dc link voltage, the $G(\theta)$ function is computed based on the equations of Table 1 in real time. Since the waveform of the $G(\theta)$ function is identical at the entire speed range, it can be characterized at steady state in a look-up table, and used as a position reference for sensorless operation at all speeds[6].

3. MODELLING OF SENSORLESS CONTYTROL OF PMBLDC MOTOR:

An Inverter fed Trapezoidal PMAC Motor drive operating in self controlled mode is called a Brushless DC(PMBLDC) Motor. The complete PMBLDC drive system consists Power conversion PWM inverter, BLDC motor and load and Speed, torque, and current controller. The exact understanding of each part is a prerequisite for analysis and prediction of the overall system operation. A simulation model can be an easy-to-design tool for a precise prediction of drive performance during transient and steady state operation. The simulation model of the complete drive is a combination of several functional and equation based modular blocks developed by using MATLAB SIMULINK. The inverter which is connected to the dc supply feeds controlled power to the motor. The magnitude and frequency of the inverter output voltage depends on the switching signals generated by the hysterisis controller. The state of these switching signals at any instant is determined by the rotor position, speed error and winding currents. The controller synchronizes the winding currents with the rotor position[7][8].

4. SIMULATION RESULTS:

A. NO-LOAD OPERATION:

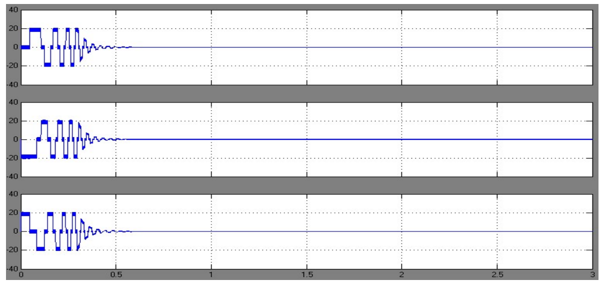

Fig.3 Current waveforms i_a, i_b, i_c for no-load operation

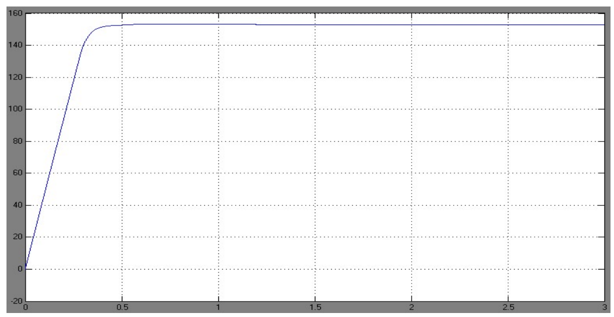

Fig.4 Speed variation of motor for no-load operation

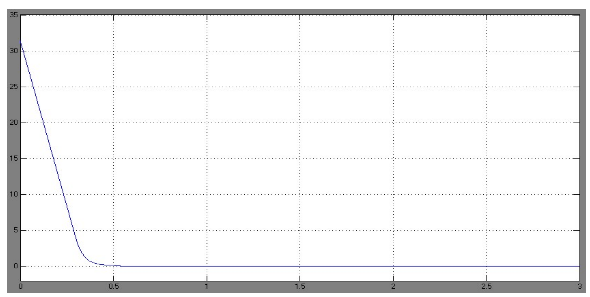

Fig.5 Electromagnetic torque developed for no-load operation

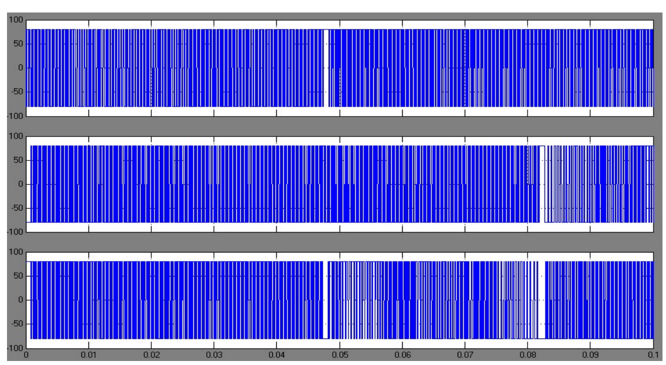

Fig.6 Voltage waveforms Va, Vb, Vc for no-load operation

B. LOAD PERTURBATION:

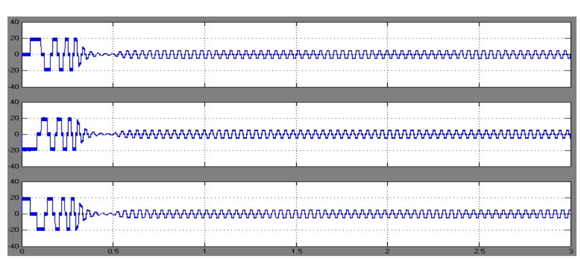

Fig.7 Current waveforms for a step change in load of 1 Nm at t=0.5sec for dc input voltage of 160V

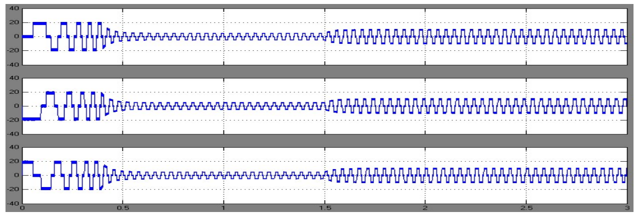

Fig.8 Current waveforms for a step change in load of 2Nm at t=1.5sec for dc input voltage of 160V

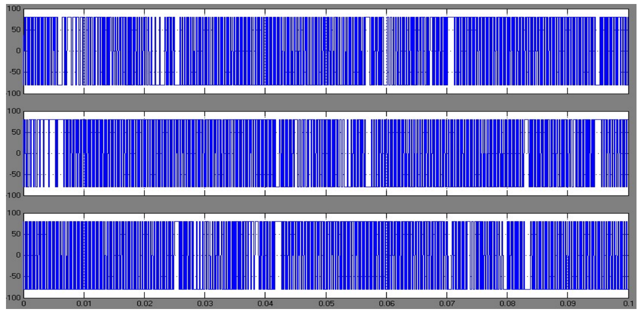

Fig.9 Voltage waveforms for a load of 1Nm with dc input voltage of 160V

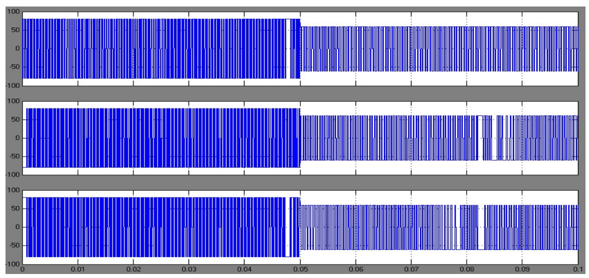

Fig.10 Voltage waveforms for a step change in load of 1Nm at t=0.05sec for dc input voltage of 160V to 120V

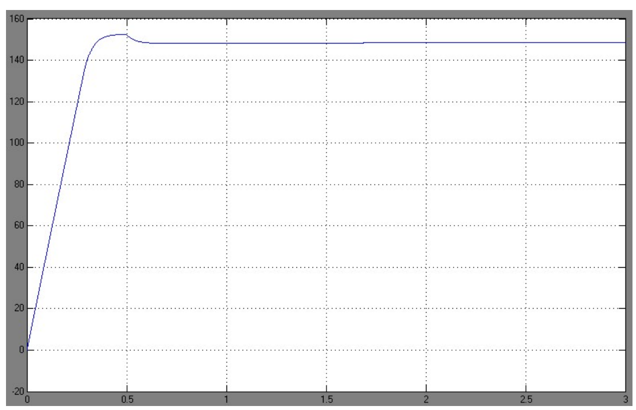

Fig. 11 Speed variation of motor for a step change in load of 1Nm at t=0.5sec for input voltage of 160V

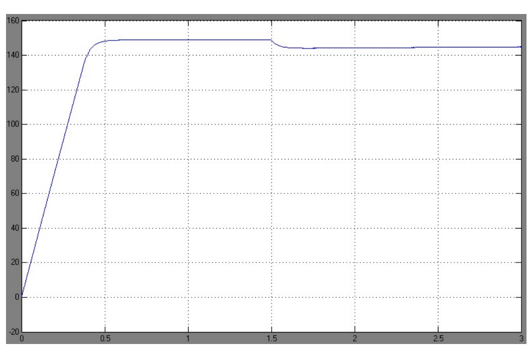

Fig. 12 Speed variation of motor for a step change in load of 1Nm to 2Nm at t=1.5sec for input voltage of 160V

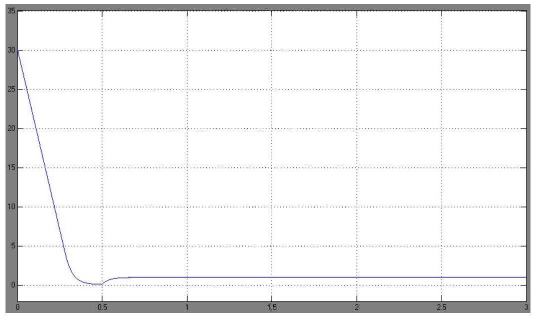

Fig. 13 Torque variation for step change in load of 1Nm at t=0.5sec input dc voltage of 160V

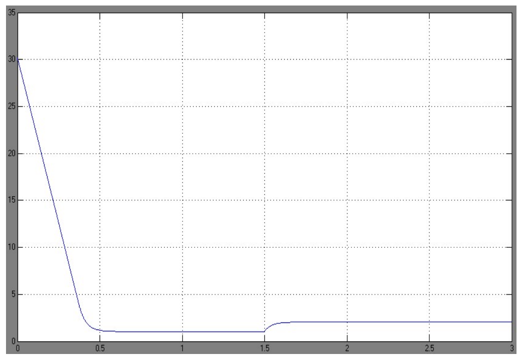

Fig. 14 Torque variation for step change in load of 1Nm to 2Nm at t=1.5sec input dc voltage of 160V

5. CONCLUSION:

Equation based Matlab/Simulink Simulation model for Permanent Magnet Brushless DC Motor is designed. Under open loop operation, the motor speed cannot be controlled to the desired level and one has to go to any of the closed loop operation for a better performance of the drive. The starting current is very high under open loop operation, which is limited to a lower value in a closed loop operation. The simulation results of sensorless control of PMBLDC drive using speed independent position are shows that it provides commutation even in transient state because of the speed independent position function.

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