

voltage equation of the machine and by integrating the applied voltage and current, flux can be estimated. From the initial position, machine parameters, and the flux linkages' relationship to rotor position, the rotor position can be estimated. This method also has significant estimation error in low speed. Improper error of parameters and sampled current is reason for accumulation error at low speeds in which the voltage equation is integrated in a relatively large period of time.

C. Back-EMF Integration Technique [5]-[6]:

In this method, position information is extracted by integrating the back-EMF of the silent phase. Integration starts when the open phase's back-EMF crosses zero. A threshold is set to stop the integration that corresponds to a commutation instant. This method also has a problem at low speeds because of the error accumulation problem.

D. Freewheeling Diode Conduction [7]:

This method uses current flowing through a freewheeling diode in silent phase. For a short period after reaching zero crossing of the back-EMF in silent phase, a tiny current is flowing through freewheeling diode; during the active phase switches are turned off under alternate chopper control. This silent phase current starts to flow in the middle of the commutation interval, which corresponds to the point where back-EMF of the open phase crosses zero. This method also has position error of commutation points in transient state. The most serious drawback of this method is the requirement of six additional isolated power supplies for the comparator circuitry to detect current flowing in each freewheeling diode.

3. The Proposed Sensorless Control Method

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 at low speed range. Also, the estimated commutation points that are shifted by 30° from zero crossing of back-EMFs have position error in transient state. The flux estimation method [3]- [4] also has significant estimation error at low speed, in which the voltage equation is integrated in a relatively large period of time. In this research, 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.

A. Modeling of the BLDC Motors

The voltage equations of the BLDC motor is derived as:

$$\left. \begin{aligned} V_a &= i_a R_a + L \frac{d}{dt} (L_{aa} i_a + L_{ab} i_b + L_{ac} i_c) + \frac{d\lambda_{ar}(\theta)}{dt} \\ V_b &= i_b R_b + L \frac{d}{dt} (L_{ba} i_a + L_{bb} i_b + L_{bc} i_c) + \frac{d\lambda_{br}(\theta)}{dt} \\ V_c &= i_c R_c + L \frac{d}{dt} (L_{ca} i_a + L_{cb} i_b + L_{cc} i_c) + \frac{d\lambda_{cr}(\theta)}{dt} \end{aligned} \right\} (1)$$

In Balanced system:

$$\begin{aligned} R_a &= R_b = R_c = R \\ L_{aa} &= L_{bb} = L_{cc} = L_s \\ L_{ba} &= L_{ab} = L_{bc} = L_{cb} = L_{ac} = L_{ca} = L_m \\ L &= L_s - L_m, i_a + i_b + i_c = 0 \end{aligned}$$

Where $V_a, i_a, R, L_s, L_m, L, \theta$ and λ_{gr} represent the phase A voltage, phase A current phase resistance, inductance, self-inductance, mutual inductance, rotor position, and Phase A flux linkage due to rotor permanent magnet flux, respectively. For surface mounted permanent magnet (SMPM) typed BLDC motors, (1) can be simplified based on (2) as:

$$\left. \begin{aligned} V_a &= i_a R + L \frac{di_a}{dt} + \frac{d\lambda_{ar}(\theta)}{dt} = i_a R + L \frac{di_a}{dt} + \frac{d(k_e f_{ar}(\theta))}{dt} \\ V_b &= i_b R + L \frac{di_b}{dt} + \frac{d\lambda_{br}(\theta)}{dt} = i_b R + L \frac{di_b}{dt} + \frac{d(k_e f_{br}(\theta))}{dt} \\ V_c &= i_c R + L \frac{di_c}{dt} + \frac{d\lambda_{cr}(\theta)}{dt} = i_c R + L \frac{di_c}{dt} + \frac{d(k_e f_{cr}(\theta))}{dt} \end{aligned} \right\} (2)$$

$$\left. \begin{aligned} &= i_a R + L \frac{di_a}{dt} + k_e \cdot \frac{d\theta}{dt} \cdot \frac{d(f_{ar}(\theta))}{dt} \\ &= i_b R + L \frac{di_b}{dt} + k_e \cdot \frac{d\theta}{dt} \cdot \frac{d(f_{br}(\theta))}{dt} \\ &= i_c R + L \frac{di_c}{dt} + k_e \cdot \frac{d\theta}{dt} \cdot \frac{d(f_{cr}(\theta))}{dt} \end{aligned} \right\} (3)$$

Since some manufacturers do not provide a motor neutral point, the line-to-line voltage equations are utilized as below:

$$V_{ab} = R(i_a - i_b) + L \frac{d(i_a - i_b)}{dt} + k_e \frac{d\theta}{dt} \cdot \frac{d\{f_{ar}(\theta) - f_{br}(\theta)\}}{d\theta} \quad (4)$$

$$V_{ab} = R(i_a - i_b) + L \frac{d(i_a - i_b)}{dt} + k_e \frac{d\theta}{dt} \cdot \frac{df_{abr}(\theta)}{d\theta} \quad (5)$$

$$V_{ab} = R(i_a - i_b) + L \frac{d(i_a - i_b)}{dt} + k_e \omega \frac{df_{abr}(\theta)}{d\theta} \quad (6)$$

Where ω and k_e stand for the speed and back-EMF constant, respectively. It is seen that $\lambda_{ar}(\theta)$ in (1) is expressed as a constant value times a periodic function that changes with rotor position as shown in (3). The $f_{abr}(\theta)$ is a line-to-line flux linkage form function that is changed by the rotor position. Now we define a function, $H_{ab}(\theta)$, as:

$$H(\theta)_{ab} = \frac{df_{abr}(\theta)}{d\theta} \quad (7)$$

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

$$H(\theta)_{ab} = \frac{1}{\omega k_e} \left[(V_a - V_b) - R(i_a - i_b) - L \left(\frac{di_a}{dt} - \frac{di_b}{dt} \right) \right] \quad (8)$$

duration of each mode in Fig. 2 (a) corresponds to 60 by electrical angles.

B. Derivation of the Speed-independent Position Function

To eliminate the speed term ω in (8), one line-to-line $H(\theta)$ function is divided by another line-to-line $H(\theta)$ function, and the divided new function is named as $G(\theta)$. For example

$$\begin{aligned} \frac{H(\theta)_{ab}}{H(\theta)_{bc}} &= \frac{\frac{1}{\omega k_e} \left[(V_a - V_b) - R(i_a - i_b) - L \left(\frac{di_a}{dt} - \frac{di_b}{dt} \right) \right]}{\frac{1}{\omega k_e} \left[(V_b - V_c) - R(i_b - i_c) - L \left(\frac{di_b}{dt} - \frac{di_c}{dt} \right) \right]} \\ &= \frac{\left[(V_a - V_b) - R(i_a - i_b) - L \left(\frac{di_a}{dt} - \frac{di_b}{dt} \right) \right]}{\left[(V_b - V_c) - R(i_b - i_c) - L \left(\frac{di_b}{dt} - \frac{di_c}{dt} \right) \right]} = G(\theta)_{ab/bc} \end{aligned} \quad (9)$$

To provide the best position information that is speed independent with high sensitivity at each commutation point, we utilize the ratio of two line-to-line $H(\theta)$ functions. From the sequential combination of two line-to-line $H(\theta)$ functions at each commutation interval, we derive the $G(\theta)$ function that is independent of speed and contains continuous position information. Fig. 1 shows the $G(\theta)$ functions ($G(\theta)_{bc/ab}$, $G(\theta)_{ab/ca}$ and $G(\theta)_{ca/bc}$) waveform based on (9).

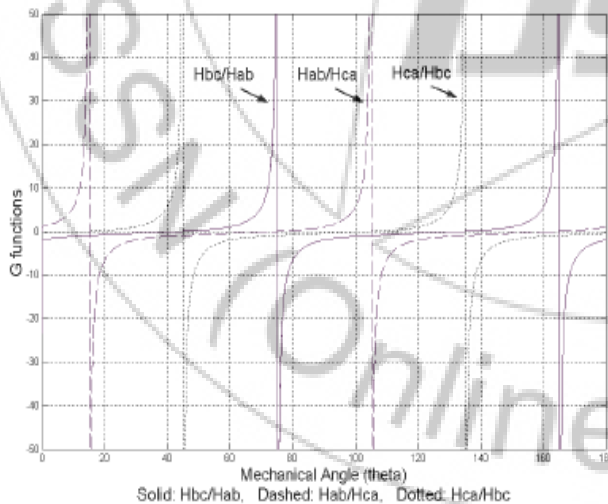


Figure 1: G-function

C. Commutation Strategy

Fig. 2 shows waveforms of the line-to-line $G(\theta)$ function, phase current and generated commutation pulse from the $G(\theta)$ function in time domain. Here, two line-to-line $H(\theta)$ functions are used in each mode as Table I. The time

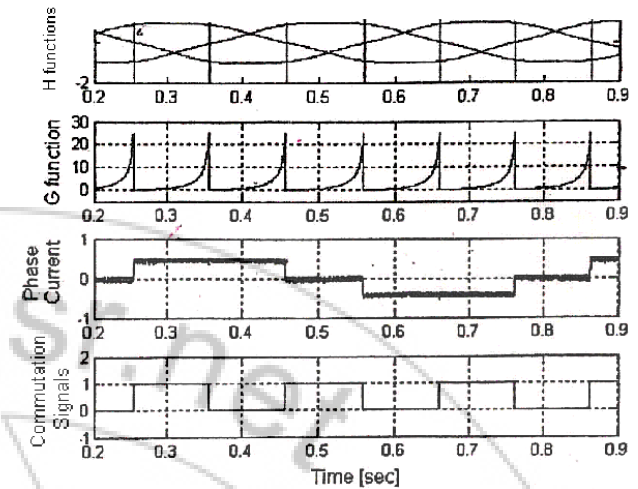


Table I shows the position estimation equations at each mode. As shown in Fig. 2 (a), at mode 1, $G(\theta)_1$ is used as a position estimation equation; after a 60° electrical angle, at mode 2, $G(\theta)_2$ is utilized. When the $G(\theta)$ function reaches a predefined threshold value, the motor is commutated as Fig.2 (d). The threshold value is defined based on the current rising time and desired advanced angle. From the sequential combination of the $H(\theta)$ functions based on Table I, the $G(\theta)$ function can be made as Fig. 2 (b).

Table- I

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

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, $G(\theta)$ function is calculated by equations of Table I 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. If the control purpose is just to follow the square wave reference current for constant torque, the commutation points that are detected at the peak point of

the $G(\theta)$ function are sufficient as position information, but for special purpose of control, for example, an advanced angle control for the field weakening operation, it is required to know more position information between commutation points Fig. 3 shows the procedure to estimate position between commutation points. From the measured current and line-to-line voltages that are calculated by multiplication of the DC bus voltage and switching status, $G(\theta)$ function is calculated at each mode. Then, position is estimated by the look-up table of the characterized $G(\theta)$ function.

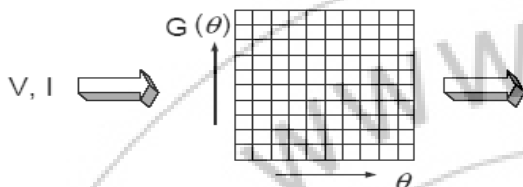


Figure 3: Estimation of the position using the characterized G function

E. Current Control

To control currents, a simple PI or hysteresis controller can be used for the proposed sensorless method. Also, to calculate line-to-line voltages in equations of Table I, the three phase activated current control is utilized. It means that a silent phase current is controlled as zero.

F. Starting Procedure

In typical sensorless operation of the BLDC motor, the forced alignment of the rotor is a way of setting an initial position [5]-[7]. Two phases are excited to cause the rotor to shift and lock into position. If the rotor is not in the desired position, the forcing torque from the excited phases causes it to rotate and stop at the desired position. After energizing two of the three motor phases for enough time to ensure the rotor will lock into position, the next commutation signal advancing the switching pattern by 60 degrees is given, then immediately the proposed sensorless algorithm using the $G(\theta)$ function is applied to detect the next commutation instant. The 60 movements make enough speed to detect the commutation instant using the position estimation equations in Table I. After the first detection of the commutation point, speed control is possible using the estimated speed from time duration of each commutation point.

4. Simulation Results

Simulation results of the proposed sensorless method are shown in figure 4 below. Figure 4(a) shows the Individual G- function, Figure 4(b) shows the phase current, Figure 4(c) shows the Commutating signal. Figure 4(d) shows the back EMF, Figure 4(e) shows the combined G – function.

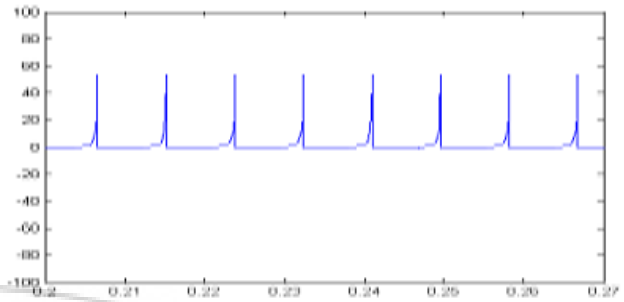


Figure 4(a)

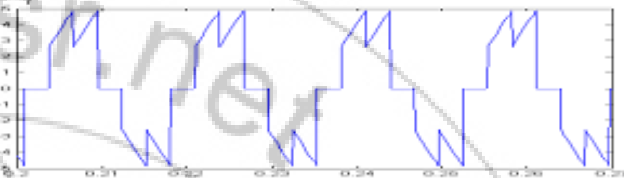


Figure 4 (b)

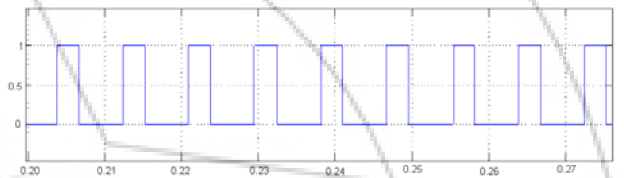


Figure 4 (c)

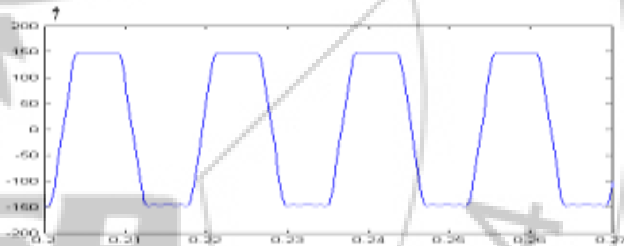


Figure 4 (d)

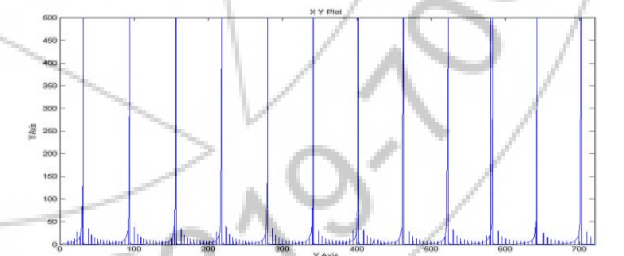


Figure 4 (e)

5. Conclusions

This paper presented a novel sensorless drive method for BLDC motors. This technique makes it possible to detect the rotor position over a wide speed range from near zero to high speed. The capability of position detection at around 1% of the rated speed makes the starting procedure much simpler than conventional methods. Also, the proposed approach provides a precise commutation pulse even at transient state because of the speed independent characteristic of the G function. From the simulation and

experimental results, the validity of the developed sensorless drive technique using the new speed independent function is successfully verified. Based on the successful experimental results, the proposed sensorless algorithm with wider speed range will be implemented in various industrial applications.

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