A Study on the Advanced Twelve Step Sensor-Less Control of BLDCM Using FOC

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***Abstract*-The zero crossing detection is essential in twelve sensors-less control using back-EMF. To increase output power of Brushless DC motor (BLDCM), traditional twelve step control has extended active angular period. It has drawback which become unstable the performance of the drive system in rated load condition because a period for detecting zero crossing point of terminal voltage is reduced. To solve this problem, this paper proposes the advanced twelve step sensor-less control of a BLDCM using field oriented control (FOC), which combines the traditional twelve step sensor-less drive scheme and single shunt three phase current reconstruction algorithm. The effectiveness of this proposed control is verified by the simulation and experiment result according to the comparison of the output characteristics between the traditional and proposed control.**

Keywords-sensor-less control; twelve steps; BLDCM; FOC

I. INTRODUCTION

In recent year, the 120° drive and 180° drive have been mostly applied to BLDCMs [1]-[3]. The output torque of 180° drive scheme is greater than 120° drive scheme. However, the detection of zero crossing point for identify the rotor position is difficult because the windings of all phase are always conducted. As a result, sensor-less drives are based on the 120° drive scheme [4]. The torque ripple and output torque of the 120° drive scheme are larger and smaller than the 180° drive. To compensate this problem, Saha *et al.* and Wang *et al.* proposed a 150°, a 165° and 168.75° sensor-less drive scheme, respectively [5]. The 165° and 168.75° sensor-less drive schemes are to extend active angular period. In terms of output characteristics, the performance of 168.75° sensor-less drive scheme is better than other drive scheme. However, it has drawback which become unstable the performance of the drive system in rated load condition because a period for detecting zero crossing point of terminal voltage is reduced. To solve this problem, this paper proposes the advanced twelve step sensor-less control of a BLDCM using field oriented control (FOC) [6], which combines the traditional twelve step sensor-less drive scheme and single shunt three phase current reconstruction algorithm [8].

II. TRADITIONAL TWELVE STEP SENSOR-LESS CONTROL

A. *Original Twelve Step Sensor-Less Control Drive Scheme*

Fig. 1. shows back-EMF detection and phase current according to original control and traditional extended control. It is controlled using a combination 120° and 180° drives. 120° drive mode is always conducts two phase of BLDCM and leaves the rest phase in the electrical degree of 30° intervals. It is possible to detect back-EMF by measuring its terminal voltage. 180° drive mode conducts three phase of BLDCM from zero crossing point to 30°. During one period of 360°, this commutation is repeated six times, respectively. The 150° drive have the advantage of the 120° drive scheme to detect the back-EMF and the advantage of the 180° drive scheme to improve the torque constant [7].

B. *Traditional Twelve Step Extended Sensor-Less Control Drive*

To extend active angular period, we increase the conducting interval for some more α in the 180° drive mode (see Fig. 1). This method is similar to that of the original twelve step control with the exception of delay angle α.

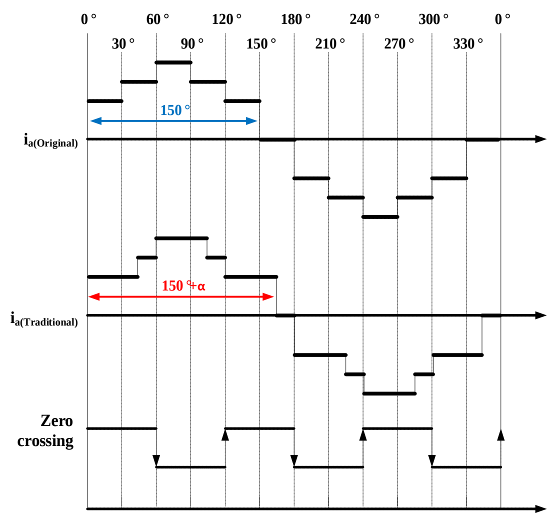


FIGURE I. ORIGINAL AND TRADITIONAL TWELVE STEP SENSOR-LESS CONTROL.

III. PROPOSED TWELVE STEP SENSOR-LESS CONTROL

A. *Twelve step FOC Drive Scheme*

The block diagram of the drive system with the proposed control method is shown in Fig. 2. The rotor position is divided to 6 sector through detection of back-EMF.

In the 120° drive mode period, if the transistors switched sufficiently high frequency, the motor inductance keeps the current waveform smooth and the motor responds to the average applied voltage. Therefore, the rotation speed is proportional to the applied voltage. The average voltage V_{ab} is given by

$$V_{ab} = \frac{V_s \times t_{on} + 0 \times (t_s - t_{on})}{t_s} = \frac{t_{on} V_{dc}}{t_s} = dV_{dc} \tag{1}$$

Where, t_s, t_{on} are the switching period and switch on period and d is the ratio t_{on}/t_s. Since $i_c=0$ during two phase conducting period, we have $i_b=-i_a$ and therefore $di_b/d_t=-di_a/d_t$. Then if we write $e_{ab}=e_a-e_b$,

$$v_{ab} = v_a - v_b = e_{ab} + 2Ri_a + 2(L-M)\frac{di_a}{dt} \qquad (2)$$

When the no-load conditions of BLDCM, the phase current ratio is zero because the current is constant. In the case $di_a/d_t=0$ and from (1) and (2), the required duty-ratio d is given by

$$d = \frac{e_{ab} + 2RI_{sp}}{V_{dc}} \qquad (3)$$

Where, I_{sp} is the required saturation current in no-load conditions. The required duty-ratio d is the q axis current reference value of the proposed control.

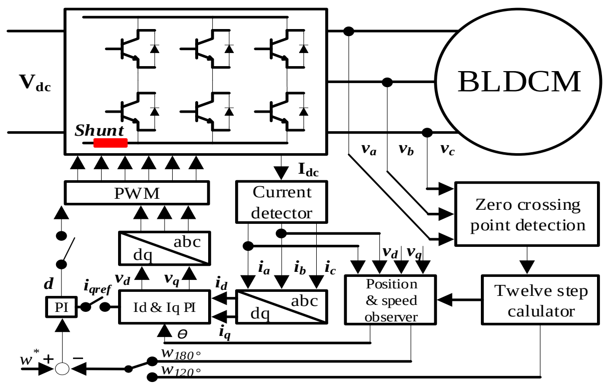


FIGURE II. BLOCK DIAGRAM OF PROPOSED CONTROLLER.

In the 180° drive mode period, the three phase stator currents are measured from single shunt resistor. These measurement provide values i_a, i_b and i_c is calculated by

$$i_a + i_b + i_c = 0 \qquad (4)$$

The three phase currents are converted to two axis system. The two axis coordinate system is rotated to align the rotor flux using a transformation angle calculated at the last iteration of the twelve step calculator. This conversion provides the i_d and i_q variables from i_a and i_b. i_d and i_q are input PI controllers and the output of the controllers provide v_d and v_q, which are voltage vector that will be sent to the motor. The electrical angle of the rotor position is estimated where i_d, i_q, v_d and v_q. Then, the v_d and v_q, value are transformed back to the three phase value v_a, v_b and v_c. Finally, the three phase voltage values are used to calculate PWM generator.

IV. Simulated and Experimental Results

A. Simulated Results

1) Simulated results of traditional control. To analysis the output characteristics of BLDCM based on the traditional and proposed control, the coupling-simulation of FEM commercial software J-MAG and PSIM is essential. We analysed using FEM to define the specifications of BLDCM that will be used in PSIM program directly. The specifications of BLDCM are listed in Table I.

TABLE I. SPECIFICATIONS OF BLDCM.

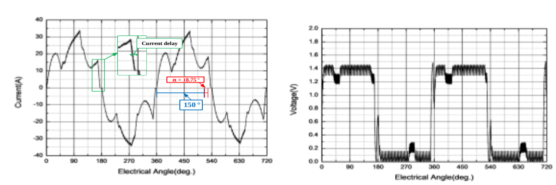
Item	Unit	Values
Stator resistance	Ω	0.09
Inductance	mH	0.199
Supply voltage	V_{dc}	24
Rated output	W	400
Rated torque	Nm	2.06
Rated speed	rpm	1850
Moment of inertia	$kg \cdot m^2$	181.869e^{-6}
Number of pole	$pole$	4

In case of traditional twelve step extended sensor-less control at rated load condition, the waveform of phase current i_a is shown in Fig .3 (a). The reference value of active angular angle is 18.75°. However, phase current is delayed at the end of this 180° drive mode interval because of the finite inductance and back-EMF of BLDCM. The results cause the zero crossing point detecting failure because a period for detecting zero crossing point of terminal voltage is reduced (see Fig. 3 (b)). In addition, the torque ripple and loss of the three phase inverter becomes large due to the current delay. Therefore, there is a need for a current control to prevent the current delay.

2) Simulated results of proposed control. In case of proposed twelve step sensor-less control at rated load condition, the waveform of phase current i_a is shown in Fig .4 (a). The reference value of active angular angle 18.75° is a same as the traditional control. The delay of the phase current i_a is minimized due to current control of FOC through the estimated rotor position and the calculated phase current. It has advantages which become stable the performance of the drive system in rated load condition because a period for detecting zero crossing point of terminal voltage is constant (see Fig. 4 (b)).

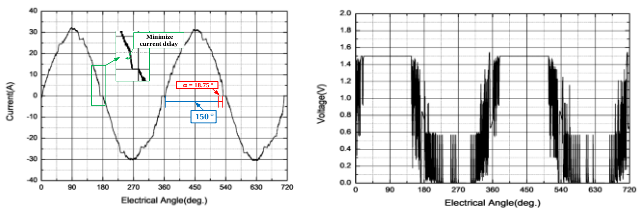
B. Experimental Results

To validate the proposed twelve step FOC control, the experimental setup is illustrated in Fig. 5. The current-regulated power FET three-phase voltage fed inverter and BLDCM for the water circulation device are available for the experimental study. The control system is implemented by a 16-bit dsPIC type dsPIC33EPMC204 operating with a clock frequency of 80 MHz and sampling interval is 50 µs for both the twelve step and FOC controls. The terminal voltage and phase current of the BLDCM are sensed by probes, isolation device and output torque is measured from torque sensor, indicator and displayed using an oscilloscope.



(A) (B)

FIGURE III. THE SIMULATED PHASE CURRENT AND TERMINAL VOLTAGE CURVES WITH TRADITIONAL EXTENDED TWELVE STEP CONTROL AT 1850RPM, 2.06NM. (A) PHASE CURRENT (B) TERMINAL VOLTAGE.



(A) (B)

FIGURE IV. THE SIMULATED PHASE CURRENT AND TERMINAL VOLTAGE CURVES WITH PROPOSED TWELVE STEP CONTROL AT 1850RPM, 2.06NM. (A) PHASE CURRENT (B) TERMINAL VOLTAGE.

Fig. 6 shows the experimental phase current and terminal voltage curves with for BLDCM with the proposed twelve step sensor-less control using FOC at 1850rpm, 2.06Nm. There is no change except a little waveform distortion. The peak to peak value of phase current is a little larger than that of the simulated one. The peak to peak values of the phase current the traditional and proposed control are 34.12A and 32.05A, respectively. The phase peak to peak current value of the proposed control significantly is reduced compare with the phase current for traditional control because it control the phase delay current. This is advantageous at low noise and low vibration operation of the BLDCM.

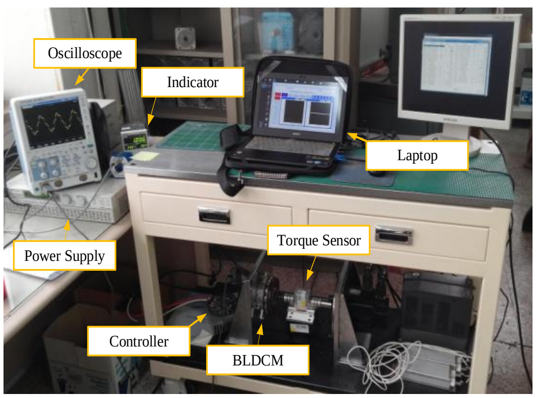


FIGURE V. EXPERIMENTAL SETUP.

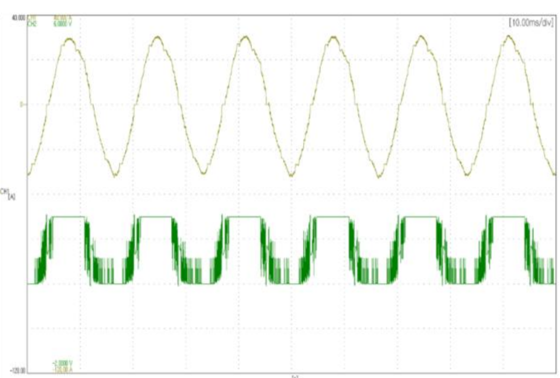


FIGURE VI. THE EXPERIMENTAL PHASE CURRENT AND TERMINAL VOLTAGE CURVES WITH FOR BLDCM THE PROPOSED TWELVE STEP FOC SENSOR-LESS CONTROL AT 1850RPM, 2.06NM.

Fig. 7 shows the polar coordinate of the experimental output torque responses for BLDCM with/without the proposed twelve-step sensor-less control using FOC. These experimental curves are similar to the simulated ones. The experimental torque contain high order harmonics that are caused by other unexpected disturbance, such as asymmetric fixing, linear bearing disturbance, friction force, wind disturbance, and so on. Whatever, the magnitudes of the results are in good agreement. The value of the torque ripple with this proposed control algorithm is significantly reduced compared with the torque ripple for the BLDCM system without the proposed control. According to the simulated and experimental results, we obtain that this proposed control has good effects on the reduction of the torque ripple. The detail results are listed in Table II. THD of phase current of traditional and proposed control are 30.96% and 5.89%, respectively. TRF of traditional and proposed control are 72.74% and 21.22%, respectively. THD and TRF of the proposed control are as small as 25.07% and 51.52% compared to the traditional control. This means that the fluctuation component is constrained effectively by the algorithm of the proposed twelve-step sensor-less control using FOC.

TABLE II. COMPARISON OF THE TORQUE RIPPLE AND THD, ATED SPEED = 1850[RPM], LOAD TORQUE = 2.06[NM].

Item	Traditional °	Proposed
THD(%)	30.96	5.89
TRF(%)	72.74	21.22

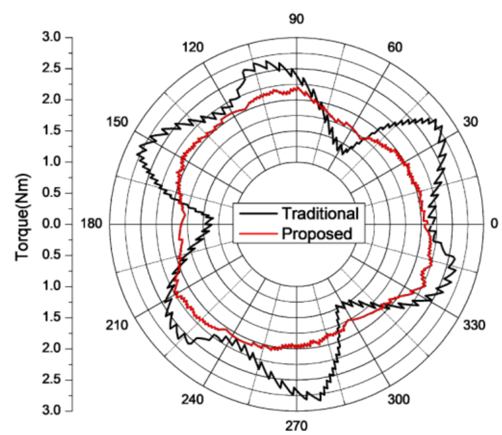


FIGURE VII. COMPARISON OF EXPERIMENTAL TORQUE RIPPLE RESPONSES FOR BLDCM WITH/WITHOUT ADVANCED TWELVE STEP SENSOR-LESS CONTROL AT 1850RPM 2.06NM.

V. CONCLUSION

Traditional twelve step extended sensor-less control has drawback which become unstable the performance of the drive system in rated load condition because a period for detecting zero crossing point of terminal voltage is reduced. To solve this problem, this paper proposes the advanced twelve step sensor-less control of a BLDCM using FOC, which combines the traditional twelve step sensor-less drive scheme and single shunt three phase current reconstruction algorithm. Compared with the conventional control methods, proposed control method is far better in output characteristics.

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