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Load-adaptive 180-Degree Sinusoidal Permanent-Magnet Brushless Motor Control Employing Automatic Angle Compensation

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** Regular Paper*

Abstract**:** This paper reports a sinusoidal 180° drive for a permanent magnet (PM) brushless motor employing automatic angle compensator to suppress the driving loss during the wide-range load operation. The proposed drive of the sinusoidal 180° PM Brushless motor reduced the amplitude of the 3-phase current by compensating for the lead-angle of the fundamental waves of the 3-phase PWM signal. The conventional lead-angle method was implemented using the fixed angle or memorized table, whereas the proposed method was automatically compensated by calculating the angle of the current and voltage signal. The algorithm of the proposed method was verified in a 30 W PM brushless motor system using a PSIM simulator. The efficiency of the conventional method was decreased 90 % to 60 %, whereas that of proposed method maintained approximately 85 % when the load shift was 0 to 0.02 N·m. Using an FPGA prototype, the proposed method was evaluated experimentally in a 30 W PM brushless motor system. The proposed method maintained the minimum phase RMS current and 79 % of the motor efficiency under 0 to 0.09 N·m load conditions. The proposed PM brushless motor driving method is suitable for a variety of applications with a wide range of load conditions.

Keywords**:** PM Brushless Motor, Motor Control, Automatic Angle Compensation

1. Introduction

Permanent magnet (PM) brushless DC and AC motors have been used in a variety of industries and consumer applications. The increasing attention on global warming and energy conservation has led to a demand for applications with high efficiency and low cost.

The PM brushless motor can be divided into two types: BLDC and BLAC [1, 2]. The BLDC motor system has considerable attention for consumer applications because of the low cost and simple circuit design. The 120° control of BLDC motor normally drives based on the square wave current using the 60° intervals of the position signal, but the motor has weaknesses, such as torque ripples and acoustic noise [3]. The BLAC motor system has developed from the induction motor control, which has high performance and reliability [4]. Vector control of the BLAC motor system is driven by analyzing on the d-q axis, but it requires a high-performance microprocessor due to the computational complexity.

The 180° sinusoidal PM brushless motor is merged with the 120° motor and FOC control, and it controls based on the 60° intervals of the position signal and drives the sinusoidal wave current. The driving circuits are relatively simple, and noise and torque ripples are reduced [5]. On the other hand, the phase-difference of the voltage and current occurs in a range of load applications, which increases the phase-current and copper loss. In an effort to address these problems, an analysis of the phase-difference and lead-angle control methods was performed [6, 7]. The

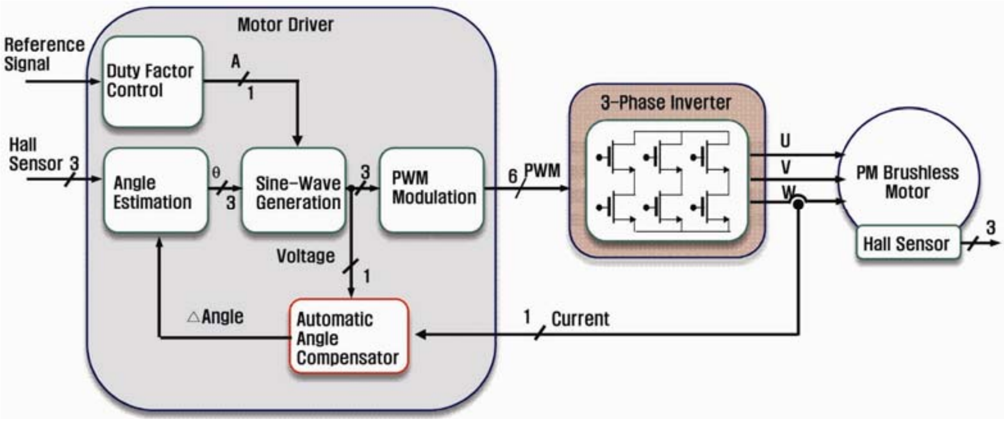

Fig. 1. Top-level configuration of the proposed PM brushless motor system.

conventional lead-angle method is implemented using the fixed angle or memorized look-up table.

This paper proposes a sinusoidal 180° drive for a PM brushless motor employing automatic angle compensator to suppress the driving loss during the wide-range load operation. The proposed drive of the sinusoidal 180° PM brushless motor reduced the amplitude of the 3-phase current by compensating for the lead-angle of the fundamental waves of the 3-phase PWM signal. Using an FPGA prototype, the proposed method was evaluated experimentally in a 30 W PM brushless motor system. The proposed method maintained the minimum phase *root mean square* (RMS) current and 79 % motor efficiency under 0 to 0.09 N·m load conditions.

2. System Architecture

Fig. 1 shows the top-level structures of the proposed PM brushless motor system. The PM brushless motor system has three parts in the motor driver, inverter and motor. The motor driver consists of an angle-estimation and PWM modulator. The angle-estimation calculates the detailed angles between each interval of the 60° hall-sensor signal and the angle can be converted to a sine-wave using the memorized look-up table. The amplitude of the sine-wave can be controlled by the duty factor and a S-PWM is generated. The structure of the proposed system is added to the automatic angle compensator, which uses one of the phase current and fundamental waves of the 3-phase PWM modulator.

3. Main Algorithm

3-phase analysis of a PM brushless motor can be described briefly, as shown in Fig. 3. The mathematical model can be expressed as

$$\begin{bmatrix} V_u \\ V_v \\ V_w \end{bmatrix} = \begin{bmatrix} R + L\frac{d}{dt} & 0 & 0 \\ 0 & R + L\frac{d}{dt} & 0 \\ 0 & 0 & R + L\frac{d}{dt} \end{bmatrix} \begin{bmatrix} I_u \\ I_v \\ I_w \end{bmatrix} + \begin{bmatrix} e_u \\ e_v \\ e_w \end{bmatrix} \quad (1)$$

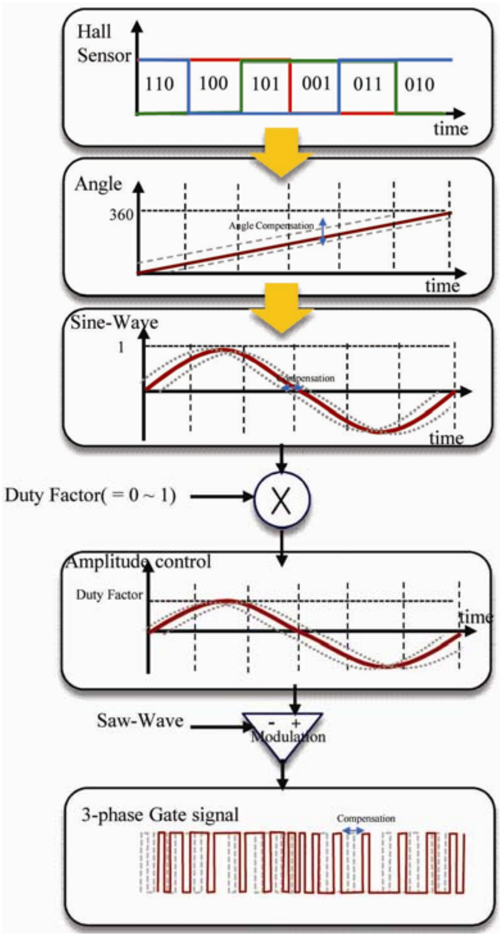

Fig. 2. Signal wave-form of 180° sinusoidal PM brushless motor drive.

where R is the stator resistance, L is the stator winding inductance, and $I_{u,v,w}$, $V_{u,v,w}$, $e_{u,v,w}$ are the phase-current, phase-voltage and *back-electromotive force* (BEMF), respectively.

Assume a motor of a 3-phase parameter has symmetrical structures, a 1-phase equation can be described as follows:

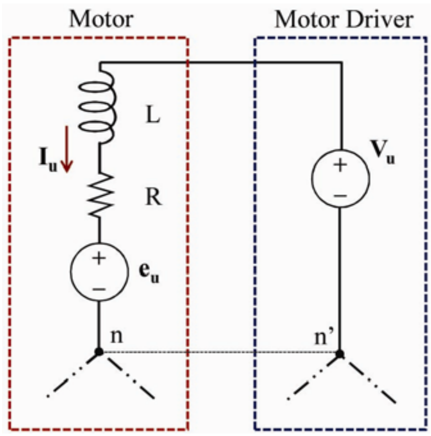

Fig. 3. 1-Phase circuit of a PM brushless motor.

$$V_u = (R + L\frac{d}{dt})I_u + e_u \qquad (2)$$

In the case of 180° sinusoidal control, all the signals have the same frequency of sinusoidal wave and the equation is transformed by phasor theory as follows:

$$V = ZI + E \ \ , (Z = R + jwL) \qquad (3)$$

where Z is the impedance of motor parameters and *w* is the electrical angular velocity. The amplitude of the phase-current (I) depends on the relationship of the phase-voltage (V) and BEMF (E) as follows:

$$|I|\angle\theta_i = \frac{|V|\angle\theta_v - |E|\angle\theta_e}{|Z|\angle\theta_z} \qquad (4)$$

If the phase of voltage (θ_v) and BEMF (θ_e) is the same, the phase-current has a minimum peak value. The properties of the BEMF signal are related to the internal structure of the PM brushless motor, and it is difficult to find information on the BEMF due to the calculation complexity. The phase-voltage can be controlled by the PWM signal in the motor driver and the phase-current can detect by current sensors. If the phase of voltage (θ_v) and BEMF (θ_e) coincide, the phase of current (θ_v) can be expressed as

$$if\ \theta_v = \theta_e \Rightarrow \theta_i = \theta_v^{'} \ \ (\theta_v^{'} = \theta_v - \theta_z) \qquad (6)$$

Because the phase of the impedance (θ_z) can be calculated by the motor parameter and velocity, the magnitude of the current can be controlled by the phase-control of the phase-difference by comparing the phase of the current and voltage. The decreased magnitude of the current can reduce power consumption and improve the motor efficiency.

The automatic angle-compensation is implemented by detecting the phase difference in the phase current and phase voltage. The proposed method uses the sine-wave of the PWM modulator instead of the phase voltage. The phase compensation is performed, as shown in Figs. 4 and 5. The voltage and current are digitized by the zero-crossing detection, and the amount of the phase difference was calculated by *logic exclusive-or* (XOR). The counter extracts the duration of the XOR pulse and the direction of the phase difference is logically decided. The amplitude and direction of the phase difference is used to calculate the compensating angle. The responsibility of compensating angle is controlled by the gain and the total angle is finally decided by the addition of the angle-estimation value and compensated value.

4. Simulation Result

The algorithm of automatic angle compensator was verified in 30W of PM Brushless motor system by using a PSIM simulator. The proposed motor drive was designed by C-language block and mixed-circuits using the PSIM supported elements. Table 1 lists the motor parameters for demonstrating the proposed system.

Fig. 6 shows the simulation results of the automatic angle compensation. During motor driving, phase-difference detection was confirmed and the angle compensation was adapted for various load and velocity conditions.

Fig. 7 shows the simulation results in the case of a fixed compensated-angle as the efficiency of the conventional

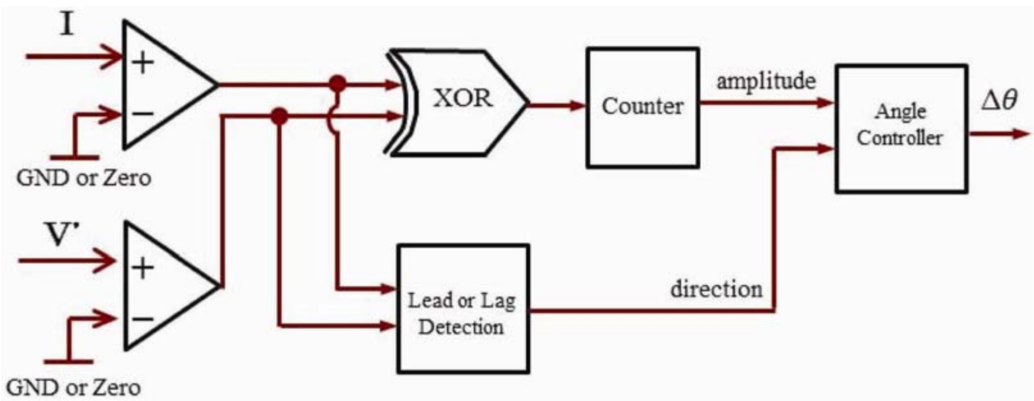

Fig. 4. Block Diagram of the automatic angle compensator.

Table 1. Simulation Conditions.

Parameters	Values
Motor Power	**30 W**
Poles	8 poles
Resistance	0.79 Ω
Inductance	1.2 mH
BEMF constant	2.5 V_{PP}/Krpm
Demonstration Tool	PSIM 9.0

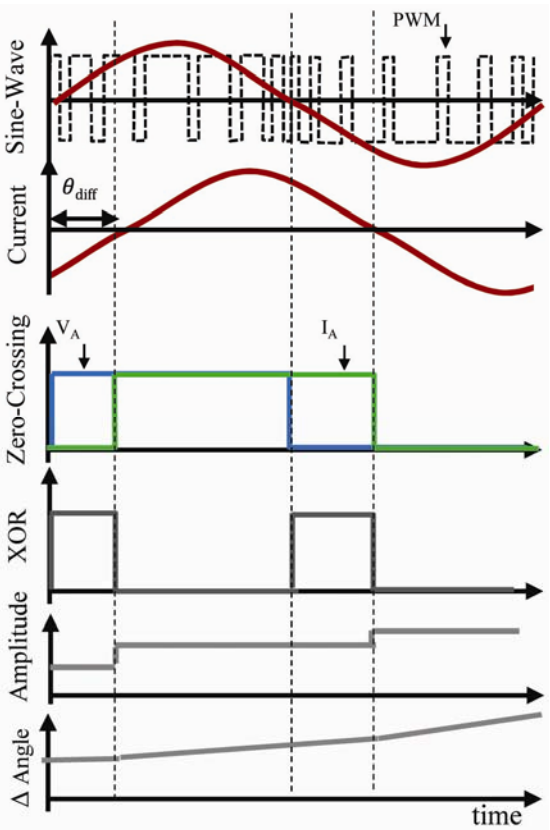

Fig. 5. Signal wave-form of the automatic angle compensation.

PM Brushless motor drive. The fixed lead-angle was applied from 10 to 33° and a load shift 0.005 to 0.02 N·m. The motor efficiency is defined as

$$P_{out} = T_m w_m \quad [W] \tag{6}$$

$$P_{copper-loss} = 3I_{rms}^2 R\,[W] \tag{7}$$

$$\eta_{motor} = \frac{P_{out}}{(P_{out} + P_{copper-loss})} \times 100 \quad [\%] \tag{8}$$

where P_{out} is the output power, T_m is the average torque, w_m is the mechanical angular velocity, I_{rms} is the RMS phase current and R is the phase resistance. The efficiency (η_{motor}) can be calculated by the output power and loss. Generally, motor losses are divided into the copper loss and iron loss [2], but the iron loss was not considered in the simulation results.

The efficiency of the conventional drive decreased approximately 90 % to 65%. The optimal fixed compensated-angle was shifted from 10 to 27° according to each load condition. Fig. 8 shows the efficiency of the proposed method and maximum efficiency of the conventional method. The efficiency of the proposed drive was maintained at approximately 85 % when the load was shifted 0 to 20 mN·m, which means the proposed method follows the optimal angle under a range of load conditions.

5. Experimental Results

An experimental evaluation of the proposed method was conducted, as shown in Table 2. The main algorithm was designed using FPGA-based digital-circuits. *Intelligent Power Module* (IPM) and *analog-to-digital converter* (ADC) and current sensor were the commercial products, as shown in Table 2. The motor evaluations were performed using the dynamometer.

The phase RMS currents of the experiment drives were measured, as shown in Fig. 9, at a fixed compensation angle of 19, 22, 25° and automatic compensation. The automatic

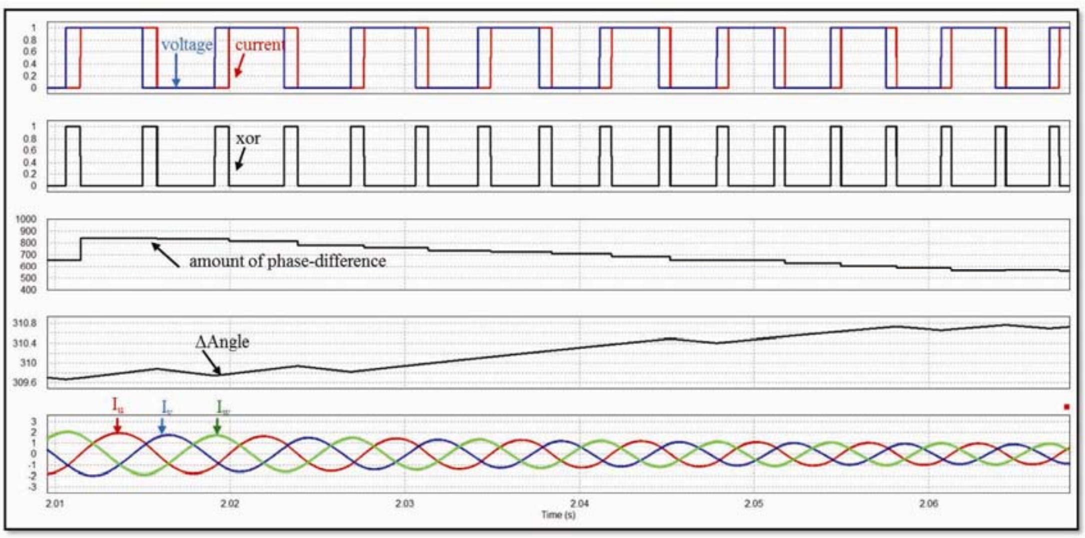

Fig. 6. Simulation wave of automatic angle compensation.

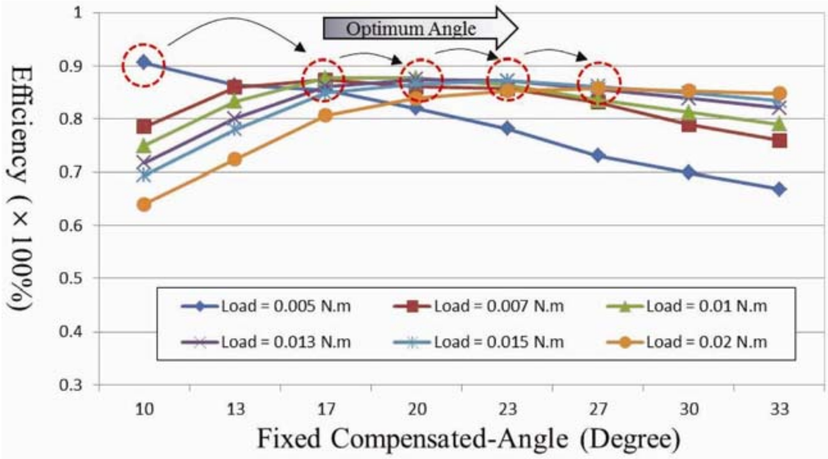

Fig. 7. Efficiency of PM Brushless motor using fixed compensated-angle.

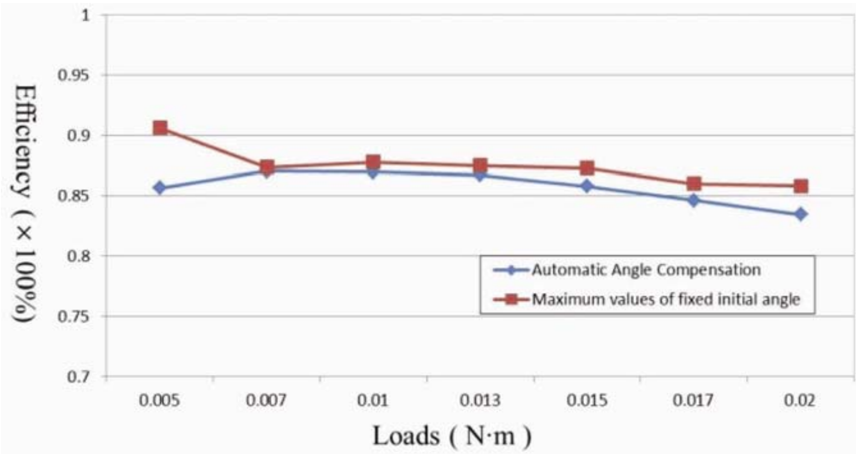

Fig. 8. Efficiency of PM Brushless motor using proposed method and maximum value of fixed initial angle.

Table 2. Experimental Conditions.

Parameters	Values
Motor Power	**30 W**
Poles	8 poles
Resistance	0.79 Ω
Inductance	1.2 mH (SPMSM)
BEMF constant	2.5 V_{PP}/Krpm
Development Tool	FPGA (Altera Cyclone II)
IPM	R_{DS} = 80mΩ, MOSFET Texas Instruments DRV8312
ADC	10-bit parallel SAR Texas Instrument TLV1571
Current Sensor	5 A range, 1mV/1mA resolution Winson WCS2705

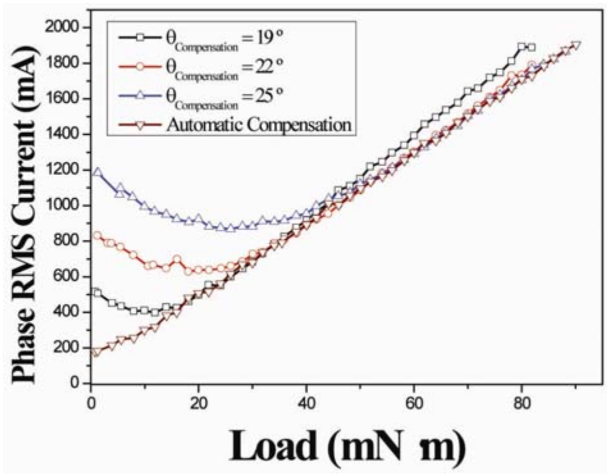

Fig. 9. Measurement results of the Phase RMS Current.

method maintained the minimum phase RMS current whereas the conventional methods had a relatively high current under low or high load conditions.

Fig. 10 shows the motor efficiency of the experimental result. The automatic compensation method closely tracked the maximum value of the conventional methods. The proposed system maintained 79 % motor efficiency

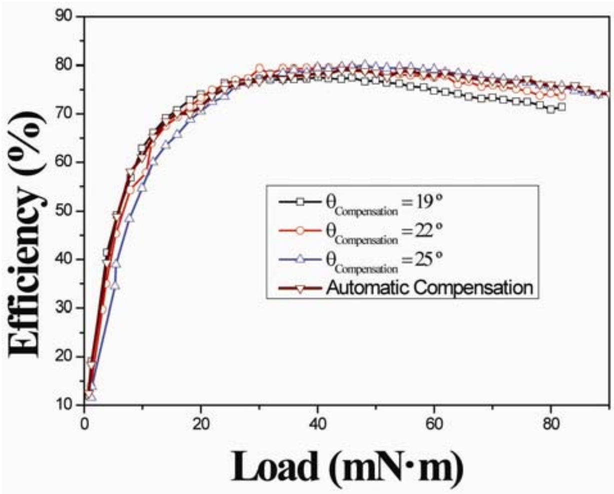

Fig. 10. Measured Motor Efficiency.

under 0 to 0.09 N·m load conditions.

6. Conclusion

This paper proposed and demonstrated a 180° sinusoidal drive for a PM brushless motor using an automatic angle compensator. The algorithm of the proposed method was verified in a 30 W PM brushless motor system using a PSIM simulator. The proposed and conventional systems were designed using FPGA-based digital circuits and evaluated using a dynamometer. The automatic angle compensation method maintained the minimum phase RMS current and maintained 79 % motor efficiency under 0 to 0.09 N·m load conditions. The proposed PM brushless motor driving method is suitable for manufacturing the motor drive SoC in a range of applications under a wide-range of load conditions.

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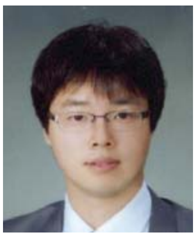

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