EVALUATION OF A SOFTWARE-CONFIGURABLE DIGITAL CONTROLLER FOR THE PERMANENT-MAGNET SYNCHRONOUS MOTOR USING FIELD-ORIENTED CONTROL

Shiyoung Lee, The Pennsylvania State University Berks Campus; Byeong-Mun Song, Baylor University;
Tae-Hyun Won, Dongeui Institute of Technology

Abstract

This paper presents a software-defined digital controller for a permanent-magnet brushless-dc motor (BLDC) using field-oriented control (FOC). The proposed controller, which improves the system performance in low-torque ripple and high performance, is introduced. The proposed FOC controller was implemented with an MC73110 motor-control chip for experimental verification. Experimental motor waveforms and simulated torque ripples with different commutation strategies were investigated. The simulation was performed with MATLAB/Simulink and SimPowerSystems library. Simulation results with the conventional trapezoidal- and FOC-commutation strategies in terms of toque ripples are explained. The FOC is easily implemented with accompanying configuration software and provides better performance than the widely-used six-step commutation in industry in regard to the complexity of the commutation circuit, torque ripple, and efficiency. In addition, the chip-based FOC controller offers major advantages in lower system development costs and reusability of the set-up code.

Introduction

The demand for high-performance digital controllers for variable-speed drive systems in many environmentally safe electric vehicle and energy efficient servo drive applications has increased rapidly [1], [2]. These digital controllers maintain the speed and torque of a motor accurately and efficiently. With advanced digital signal processing technologies in recent years, a cost-effective digital controller can be designed with field programmable gate array (FPGA) on-chip solutions for the variable-speed drives [3]. This approach allows the full digital controller to be implemented on the single-platform configuration without any hardware change. In addition, the interconnectivity between drive system networks is increased.

There are currently two common technologies for speed controllers in motor drives: analog and digital. The analog controller offers great promise for cost-effective products. However, tuning of control parameters in the analog controller has always been considered one of the major drawbacks because it directly translates to additional labor cost and manufacturing inefficiency. Furthermore, the most crucial factor in analog controllers is in poor reliability of the drive system. Thus, it is necessary to develop an intelligent software-tunable digital controller that is much more efficient and reliable.

Increased use of digital controllers will not only reduce power consumption and system size but also minimize the development cost of designing a controller [4], [5]. Thus, there have been many attempts to develop new digital controllers for motor drives [6]. Fortunately, a low-cost FPGA chip makes it possible for an intelligent controller to have an on-chip platform that can be fully digitized by FPGA programming codes [7], [8]. This yields a cost-effective and reliable speed controller for variable speed drive systems. The intelligent controller can reduce power consumption by using a real-time control algorithm to monitor variations in the load. On the other hand, it also reduces component counts by using an advanced control algorithm. Use of programming architectures can include support for multiple motor types under a single universal controller platform. This allows for easy software modification to extend the various applications.

Various drive systems have been developed and commercialized in recent years. Currently, a three-phase permanent-magnet synchronous motor (PMSM) is being widely used for accurate speed and torque control. The PMSM eliminates the commutator, making it more reliable than the dc motor. Since the PMSM produces the rotor magnetic flux with permanent magnets, it has the advantage of achieving higher efficiency than an ac induction motor. Thus, PMSMs are used in high-end white goods and appliances that require high efficiency and reliability. The advantages of the PMSM in servo drives may be summarized as follows:

- Simple rotor structure without windings
- High torque density
- High efficiency and power factor
- Maximum operating speed and maximum rotor temperatures
- Wide constant torque/power region in the torque-speed characteristics

The PMSMs, however, are not without problems. With the rotor connected to the load, there is a problem associated with low pulsation torque quality for variable-speed drive applications [3]-[6]. The problem inherently exists in the pulsating nature of torque production, which leads to torque ripple and acoustic noise. Torque pulsation can be reduced by overlap control during phase transition. For this reason, a power inverter is required to operate at a higher switching frequency in order to achieve overlap control and noise reduction. Disadvantages include high switching losses and reduction in the overall drive efficiency.

In this study, a software-defined digital controller using FOC was designed for the PMSM. For validation of the controller, a prototype controller with an MC73110 digital on-chip is implemented and demonstrated with two types of permanent-magnet brushless-dc motors. These PM motors are defined by their back-EMF waveforms: the three-phase BLDC for the trapezoidal (six-step) back-EMF (electromotive force) waveform, and the PMSM for the sinusoidal back-EMF waveform.

PMSM Drive

PMSM Drive System

Figure 1 shows a common 3-phase PMSM drive system that consists of a standard 3-phase power inverter and a PMSM. The power inverter consists of six power MOSFETs that operate in the complementary mode. This inverter provides current to drive the motor. For the BLDC, as shown in Figure 2, the motor is typically wound as a trapezoid in order to generate the trapezoidal shape back-EMF waveform. The generated torque has considerable ripple torque that occurs at each step of the trapezoidal, or six-step, commutation.

The six-step commutation typically energizes two motor phase windings at any commutation sequence. In contrast, the PMSM has a sinusoidally-distributed winding to produce the sinusoidal type back-EMF. Although the torque

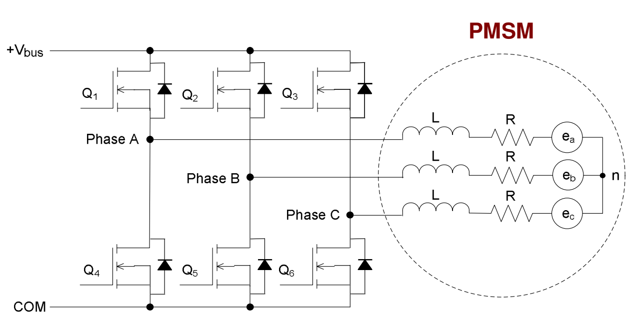


Figure 1. Three-phase full-bridge power circuit for PMSM drive

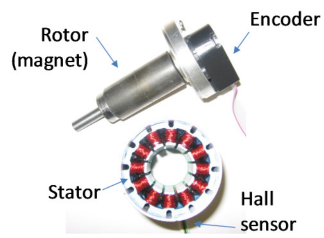


Figure 2. Photo of a BLDC structure (Moog BN23-28PM-01LHE) (Courtesy of Moog Component Group Inc.)

generated from the PMSM is smooth with much less ripple torque than with the BLDC, the peak torque production from the PMSM is lower. The sinusoidal commutation yields a sinusoidal motor current by energizing all three motor windings.

Control

The relationships between the three-phase back-EMF, motor current, and air-gap power of the PMSM are shown in Figure 3. The trapezoidal back-EMF (e_a, e_b, and e_c) has a constant magnitude of E_p during 120 electrical degrees in both the positive and negative half cycles. The air-gap power, P_a, and the electromagnetic torque are both continuous when motor currents i_a, i_b, and i_c are applied during the same period in both half cycles. The instantaneous-voltage and torque equations of a PMSM are shown in equations (1) and (2).

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \cdot \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

$$T_e = \frac{e_a \cdot i_a + e_b \cdot i_b + e_c \cdot i_c}{\omega_m} \tag{2}$$

where,

v_a, v_b, v_c : motor terminal voltages, V
i_a, i_b, i_c : motor phase currents, A
e_a, e_b, e_c : back-EMF voltages, V
R : motor winding resistance, Ω
L : motor winding inductance, H
ω_m : motor angular speed, rad/s
T_e : motor torque, N · m

Motor torque is generated by the sum of products of back-EMF and motor current. However, it is inversely proportional to motor speed, yielding high torque at low speed and low torque at high speed.

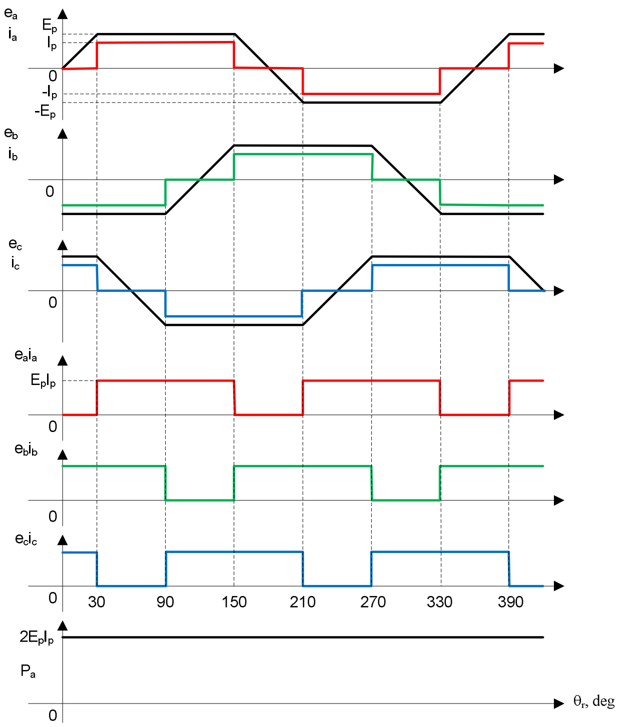


Figure 3. Relationship between back-EMF, motor current, and air-gap power for three-phase PMSM drive

Software Configurable Digital Controller

In order to drive the PMSM, an electronic commutation circuit is required. This paper deals with the position-sensor-based commutation only. The widely used commutation methods for the PMSM are trapezoidal, sinusoidal, and FOC. Each commutation method can be implemented in different ways, depending on control algorithms and hardware implementation, to provide distinct advantages.

The FOC, a control technique for operating the motor that results in fast dynamic response and energy-efficient operation at all speeds, is suitable for high-end application due to its complex design and higher processing requirements. It commutates the motor by calculating voltage and current vectors based on motor-current feedback. It maintains high efficiency over a wide operating range and allows for precise dynamic control of speed and torque. The FOC controls the stator currents represented by a space vector [1], [7]-[11]. It transforms three-phase stator currents into a flux-generating part and a torque-generating part and controls both quantities separately. The arrangement of the FOC controller resembles a separately-excited DC motor.

The simplified block diagram of an FOC for PMSM is shown in Figure 4. Phase A and B currents are measured with current sensors. The Clarke transformation converts the three-phase sinusoidal system (A, B, C) into a two-phase time variant system (α, β). It is applied to determine the motor stator current projection into the two-coordinate stationary reference frames (α, β).

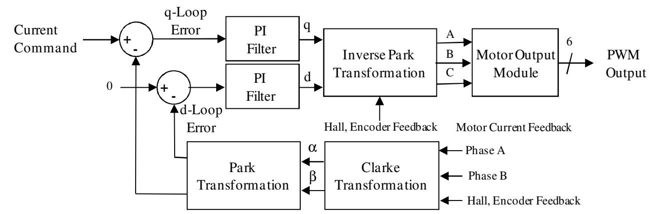


Figure 4. Simplified block diagram of an FOC

A two-coordinate time invariant system (d, q) is obtained by the Park transformation. In this system, the motor flux-generating part is d (direct) and a torque-generating part is q (quadrature), as shown in Figure 5. The (d, q) projection of the motor stator currents are then compared to their reference values: the current command for q-loop and 0 for d-loop. Both d- and q-loop errors are corrected by PI controllers.

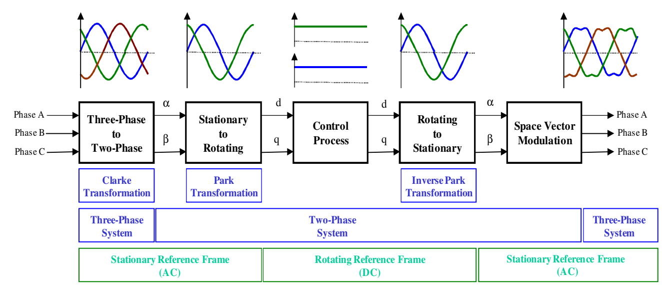


Figure 5. Various coordinate transformations in the FOC system

The inverse Park transformation generates a three-phase current command from the PI current controller. A new voltage vector is applied to PMSM using the space vector modulation (SVM) technique. It provides more efficient use of the bus voltage than the conventional sinusoidal pulse width modulation (SPWM) technique. The maximum output voltage based on the SVM is 1.15 times greater than the conventional SPWM [1]. The SVM considers the power circuit as one device, which affects all six power-switching devices because it controls the voltage vector. The characteristics of three commutation methods for the PMSM are summarized in Table I.

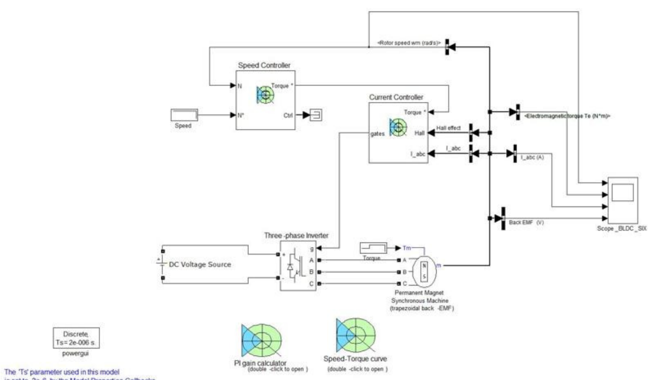
Simulation and Experimental Verification

Verification with Simulation

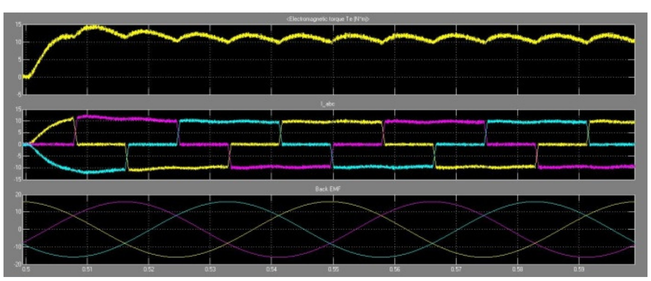
Table 1. Characteristics of various commutation methods for the PMSM

Commutation Methods	Speed Control	Torque Control		Required Feedback Devices	Algorithm Complexity
		Low Speed	High Speed		
Trapezoidal	Excellent	Torque Ripple	Efficient	Hall	Low
Sinusoidal	Excellent	Excellent	Inefficient	Encoder, Resolver	Medium
FOC	Excellent	Excellent	Excellent	Current Sensor, Encoder	High

In order to verify the generated torque ripples with combinations of two commutation strategies, simulation results with MATLAB/ Simulink software are shown in Figure 6. The simulation is performed with MATLAB/Simulink and PMSM library in SimPowerSystems. The simulation results verify that mismatch of the back-EMF waveform and commutation method produces ripple-rich torque. The torque produced with the trapezoidal commutation with PMSM has ripples as shown in Figure 6(b). Therefore, the PMSM with sinusoidal commutation is the most desirable combination for producing minimum ripple torque, as shown in Figure 6(c).



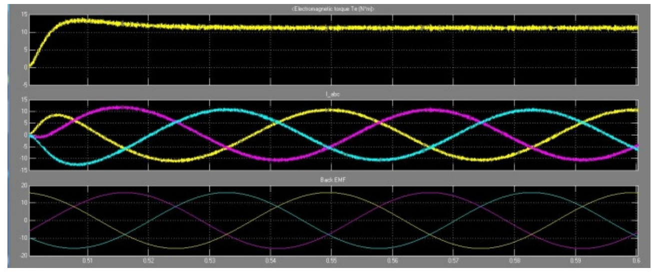
(a) MATLAB/Simulink model



(b) Trapezoidal commutation with PMSM

Experimental Verification

Experimental verification was performed with the MC73110 Developer's Kit from Performance Motion Devices, Inc. The MC73110 motor-control IC is an advanced single-chip, single-axis device that can be used to implement an



(c) FOC commutation with PMSM

Figure 6. MATLAB/Simulink model and simulation results of two commutation strategies with PMSM: torque (Top), motor current (Center), and back-EMF (Bottom)

intelligent three-phase BLDC controller based on FPGA and ASIC technologies [7], [12]. It is packaged in a 64-pin thin-quad flat pack (TQFP) measuring 12 mm by 12 mm and operates on 3.3V. It can be operated in internal velocity profile mode, velocity mode with an external analog, digital velocity command signal, or torque mode with an external torque command signal. It also can be operated as a standalone controller using pre-programmed parameters stored onto chip flash memory or through the RS-232 serial port using the Pro-Motor graphical user interface (GUI) setup software. The simplified functional block diagram of the MC73110 is shown in Figure 7.

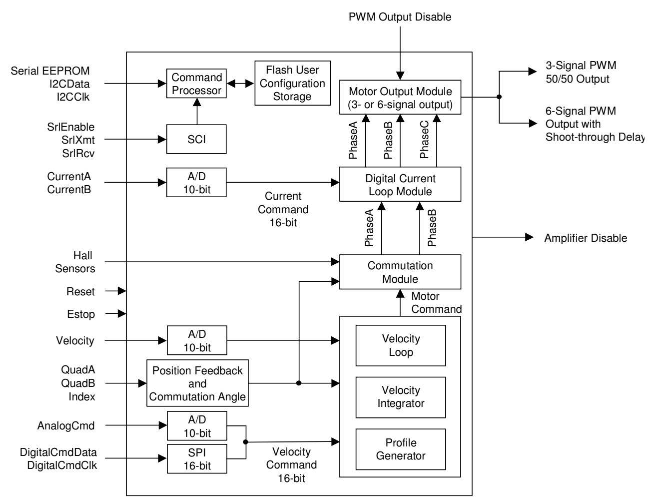


Figure 7. Simplified functional block diagram of MC73110

The various functions useful for the development of the BLDC drive are embedded in the MC73110 IC. These functions include three-phase PWM generation for a three-phase full-bridge power circuit and three-signal PWM for single-switch per-phase power circuit configuration, Hall- or quadrature encoder-based commutation, digital current and velocity loops, profile generation, emergency stop, analog velocity command, and RS-232 serial communication port. In addition to the conventional six-step with Hall-effect sensors and sinusoidal commutation with encoder, FOC is possible with MC73110 IC V2.2 and Pro-Motor V2.52. The FOC commutation provides the precise magnetic field orientation for a given rotor angle, load and speed in order to optimize overall servo drive performance.

A quadrature encoder and three Hall-effect sensors are required to implement the sinusoidal drive. The FOC drive can be realized by either a quadrature encoder or three Hall-effect sensors. The experimental setup to verify two commutation methods is shown in Figure 8. It was originally designed for an electric actuator, which contains electronic circuitry inside the enclosure along with gear assembly, as shown in Figure 8.

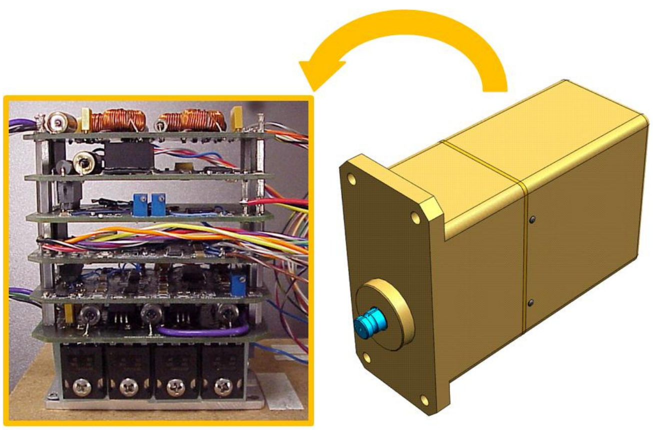


Figure 8. Experimental prototype of the proposed system (Courtesy of Moog Component Group Inc.)

The motor tested was a PMSM (Moog BN23-28PM-01LHE) and the motor terminal voltage and motor current waveforms of both trapezoidal and FOC drives are shown in Figures 9 and 10, respectively. The Hall-effect sensor-based trapezoidal drive and FOC drive provide a similar six-step current waveform, as shown in Figure 9. On other hand, an encoder-based sinusoidal drive and an FOC drive produce sinusoidal motor current waveforms, as shown in Figure 10. The line-to-line motor terminal voltages look similar with both commutation methods.

Conclusions

A new software-configurable digital controller using FOC technology for PMSM drives was presented in this paper. The main characteristics of FOC and control schemes for PMSM drives were investigated with experimental and MATLAB/Simulink simulations. The proposed controller was investigated for two commutation strategies of the PMSM operation. As a result, it was clear that FOC commutation provides smooth operation at low speeds and is highly efficient running at high speed. Furthermore, the torque ripple was significantly reduced by the proposed controller. The chip-based FOC controller offers major advantages in low servo-system development cost with no control-code development and reusability of the set-up GUI.

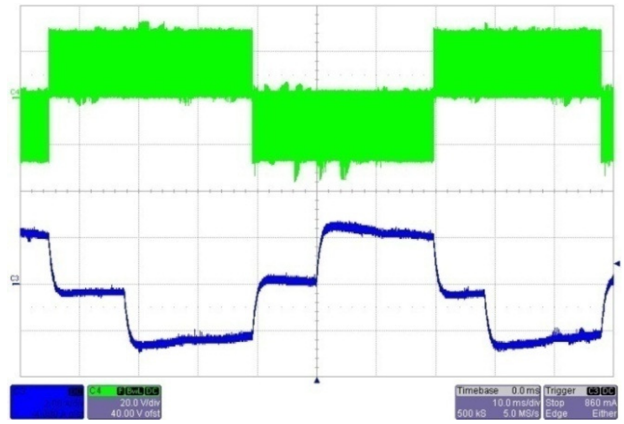


Figure 9. Relationship between motor line-to-line voltage (Top: 20V/div) and line current (Bottom: 2A/div) with six-step commutation (Horizontal: 10ms/div)

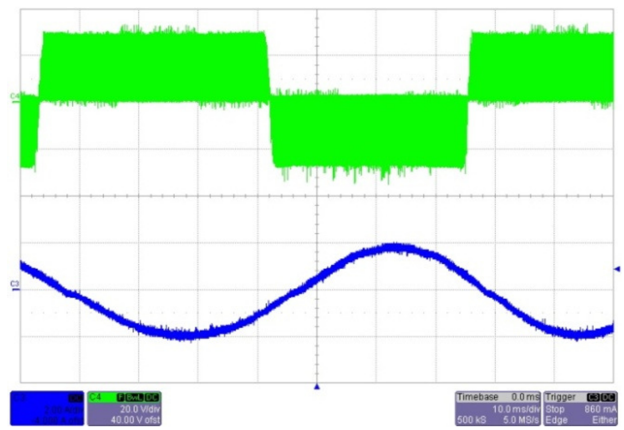


Figure 10. Relationship between motor line-to-line voltage (Top: 20V/div) and line current (Bottom: 2A/div) with FOC commutation (Horizontal: 10ms/div)

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Biographies

SHIYOUNG LEE is currently an Assistant Professor of Electrical Engineering Technology at The Pennsylvania State University Berks Campus, Reading, PA. He received his B.S. and M.S. degrees in Electrical Engineering from Inha University, Korea, his M.E.E.E. in Electrical Engineering from the Stevens Tech., Hoboken, NJ, and his Ph.D. degree in Electrical and Computer Engineering from the Virginia Tech., Blacksburg, VA. He teaches courses in Programmable Logic Controls, Electro-Mechanical Project Design, Linear Electronics, and Electric Circuits. His research interest is digital control of motor drives and power converters. He is a senior member of IEEE, as well as a member of ASEE, ATMAE, and IJAC.

BYEONG-MUN SONG received his B.S. and M.S. degrees in Electrical Engineering from Chungnam National University, Korea, in 1986 and 1988, respectively, and his Ph.D. degree in Electrical Engineering from Virginia Polytechnic Institute and State University, Blacksburg, VA in 2001. After working at the Korea Electrotechnology Research Institute for 10 years and General Atomics for 3 years, in 2004, he established his own venture company, ActsPower Technologies, San Diego, CA and served as the CEO/President and CTO. In August 2009, Dr. Song joined the Department of Electrical and Computer Engineering, Baylor University, Waco, Texas. His interests are in the design, analysis, simulation and implementation of high performance power converters, motor drives, and power electronics systems. Dr. Song is a Senior Member of IEEE.

TAE-HYUN WON, is a professor of Electrical Engineering at Dongeui Institute of Technology, Pusan, Korea. He received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from Pusan National University, Korea. He teaches Automatic Control, Electronic Circuits, and Microprocessor courses. His research interests include the sensorless control of PMSM, robust conrol of BLDC motor, and high precision and high speed motor control. He is a senior member of KIEE and KIPE.