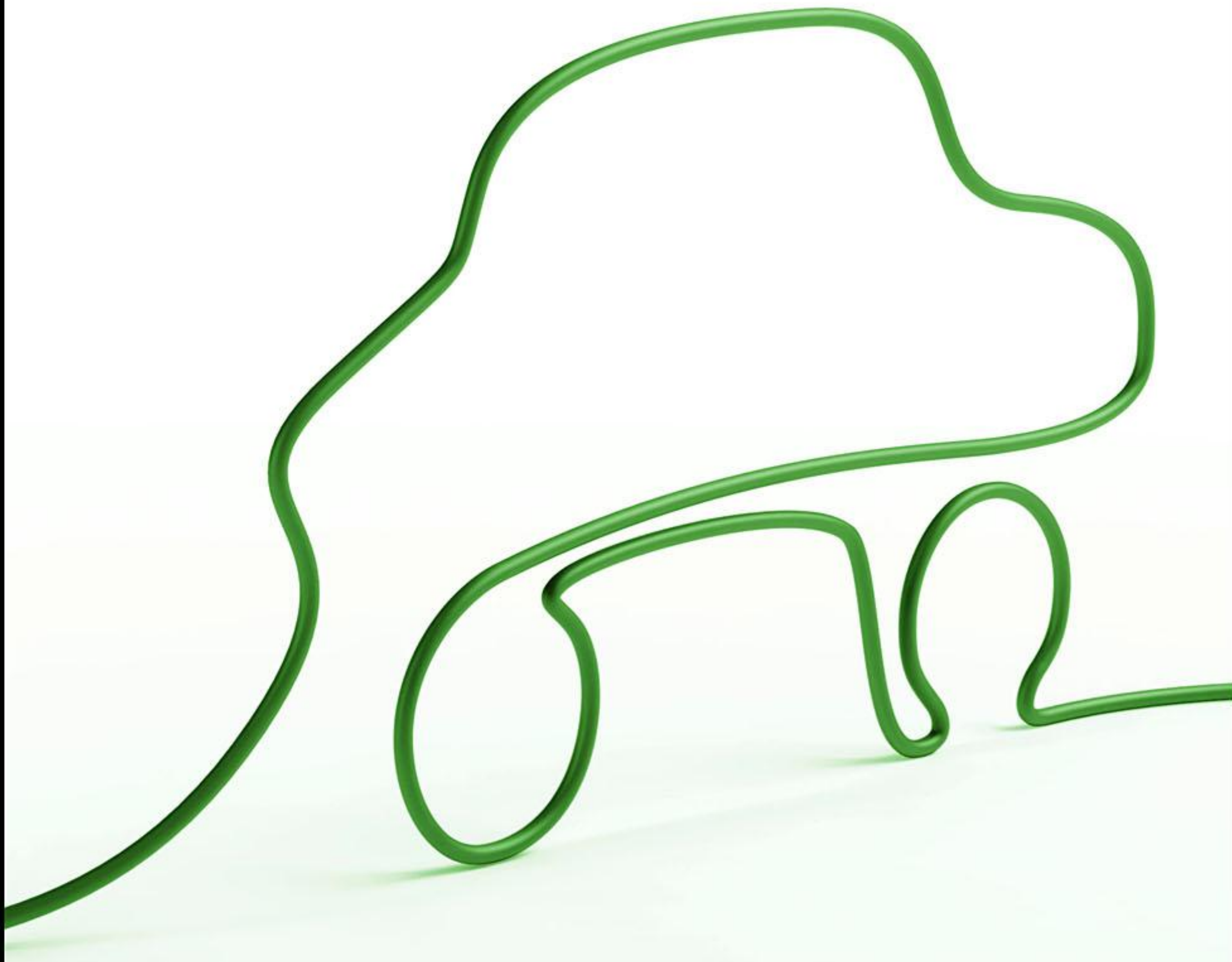
AC Motor Control *and* Electric Vehicle Applications



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Preface

The importance of motor control technology has resurfaced recently, since motor efficiency is closely linked to the reduction of greenhouse gases. Thus, the trend is to use high-efficiency motors such as permanent magnet synchronous motors (PMSMs) in home appliances such as refrigerators, air conditioners, and washing machines. Furthermore, we are now experiencing a paradigm shift in vehicle power-trains. The gasoline engine is gradually being replaced by the electric motor, as society requires clean environments, and many countries are trying to reduce their petroleum dependency. Hybrid electric vehicles (HEVs), regarded as an intermediate solution on the road to electric vehicles (EVs), are steadily increasing in proportion in the market, as the sales volume increases and the technological advances enable them to meet target costs.

Along with progress in CPU and power semiconductor performances, motor control techniques keep improving. Specifically, the remarkable integration of motor control modules (PWM, pulse counter, ADC) with a high-performance CPU core makes it easy to implement advanced, but complicated, control algorithms at a low cost. Motor-driving units are evolving toward high-efficiency, low cost, high-power density, and flexible interface with other components.

This book is written as a textbook for a graduate level course on AC motor control and electric vehicle propulsion. Not only motor control, but also some motor design perspectives are covered, such as back EMF harmonics, loss, flux saturation, reluctance torque, etc. Theoretical integrity in the AC motor modeling and control is pursued throughout the book.

In Chapter 1, basics of DC machines and control theories related to motor control are reviewed. Chapter 2 shows how the rotating magneto-motive force (MMF) is synthesized with the three-phase winding, and how the coordinate transformation maps between the *abc*-frame and the rotating *dq*-frame are defined. In Chapter 3, classical theories regarding induction motors are reviewed. From Chapter 4 to Chapter 6, dynamic modeling, field-oriented control, and some advanced control techniques for induction motors are illustrated. In Chapter 5, the benefits and simplicity of the rotor field-oriented control are stressed. Similar illustration procedures are repeated for PMSMs from Chapter 7 to Chapter 9. Chapter 9 deals with various sensorless control techniques for PMSMs including both back EMF and signal injection–based methods. In Chapter 10, the basics of PWM, inverter, and sensors are illustrated.

From Chapter 11 to 14, electric vehicle (EV) fundamentals are included. In Chapter 11, fundamentals of vehicle dynamics are covered. In Chapter 12, the concept and the benefits of electrical continuous variable transmission (eCVT) are discussed. In Chapter 13, battery EV and plug-in HEV (PHEV), including the properties and limits of batteries, are considered. In Chapter 14, some EV motor issues are discussed.

Finally, I would like to express thanks to my students, Sung Yoon Jung, Jin Seok Hong, Sung Young Kim, Ilsu Jeong, Bum Seok Lee, Sun Ho Lee, Tuan Ngo, Je Hyuk Won, Byong Jo Hyon, and Jun Woo Kim who provided me with experimental results and solutions to the problems.

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Dr. Kwang Hee Nam received his B.S. degree in chemical technology and his M.S. degree in control and instrumentation from Seoul National University in 1980 and 1982, respectively. He also earned an M.A. degree in mathematics and a Ph.D. degree in electrical engineering from the University of Texas at Austin in 1986. Since 1987, he has been at POSTECH, where he is now a professor of electrical engineering. From 1987 to 1992, he participated in the Pohang Light Source (PLS) project as a beam dynamics group leader. He performed electron beam dynamic simulation studies, and designed the magnet lattice for the PLS storage ring. He also served as the director of POSTECH Information Research Laboratories from 1998 to 1999. He is the author of over 120 publications in motor drives and power converters and received a best paper award from the Korean Institute of Electrical Engineers in 1992 and a best transaction paper award from the Industrial Electronics Society of IEEE in 2000. Dr. Nam has worked on numerous industrial projects for major Korean industries such as POSCO, Hyundai Motor Company, LG Electronics, and Doosan Infracore. Presently his research areas include sensorless control, EV propulsion systems, motor design, and EV chargers.

Chapter 1

Preliminaries for Motor Control

The DC motor offers a standard model for electro-mechanical systems, and the operational principles constitute the basics of the whole motor control theory: back EMF, torque generation, current control, torque-speed control, field-weakening, etc. The basics of DC motor and various control theories are reviewed in this chapter.

1.1 Basics of DC Machines

DC motors are popularly used since torque/speed controllers (choppers) are simple, and their costs are much lower than the inverter costs. They are still widely used in numerous areas such as in traction systems, mill drives, robots, printers, and wipers in cars. However, DC motors are inferior to AC motors in power density, efficiency, and reliability.

DC motors have two major components in the magnet circuit: field winding (or magnet) and armature winding. The DC field is generated by either field winding or permanent magnets (PMs). Armature winding is wound on a shaft. An electric motor is a machine that converts electrical oscillation into the mechanical oscillation. Although a DC source is supplied to the machine, an alternating current is developed in the armature winding by brush and commutator, i.e., the armature current polarity changes through a mechanical commutation made of brush and commutator. A picture of brush and commutator is shown in Fig. 1.1.

The basic principle of a DC motor operation is illustrated in Fig. 1.2. Fig. 1.2 (a) shows a moment of torque production with the armature coil lying in the middle of the field magnet. Fig. 1.2 (b) shows a disconnected state in which the armature winding is separated from the voltage source. Correspondingly, no force is generated. In Fig. 1.2 (c), the armature coil is re-engaged to the circuit, generating torque in the same direction. This state is the same as that in Fig. 1.2 (a) except the coil positions are switched. In some small DC machines, field winding is replaced by permanent magnets, as shown in Fig. 1.3.

Since most brushes are made of carbon, they wear out continuously. Further,

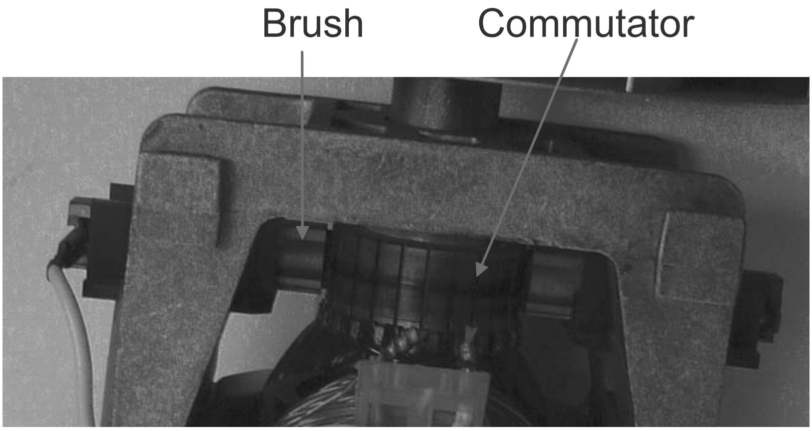

Figure 1.1: Brush and commutator of a DC machine.

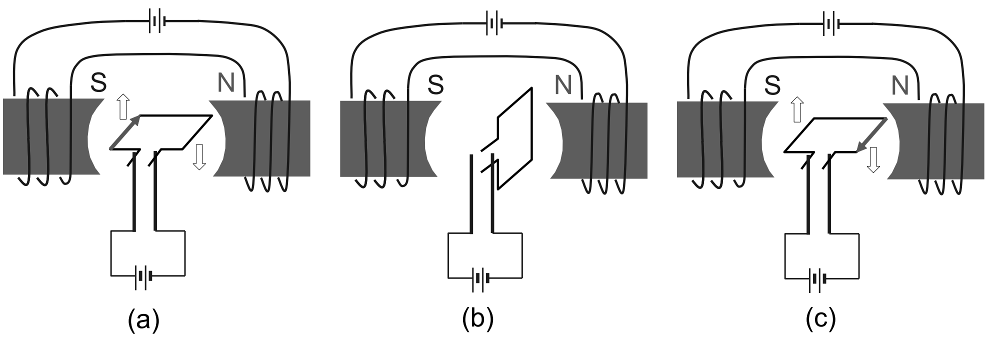

Figure 1.2: DC motor commutation and current flow: (a) maximum torque, (b) disengaged, and (c) maximum torque.

the mechanical contact causes the voltage drop, leading to an efficiency drop. DC motors require regular maintenance, since the brush and commutator wear out. As the motor size and speed increase, the commutator surface speed also increases. Further, the current density in the brush is limited and the maximum voltage on each segment of the commutator is also limited. These factors limit building a DC motor above several megawatts rating.

1.1.1 DC Machine Dynamics

In electrical rotating machines, two electromagnetic phenomena are taking place concurrently:

> **EMF generation**: When a coil rotates in a magnetic field, the flux linkage changes. According to Faraday's law, EMF is induced in the coil. It is called back EMF and described as $e_b = K_b\omega_r$, where K_b is the back EMF constant, and ω_r is the rotor angular speed.

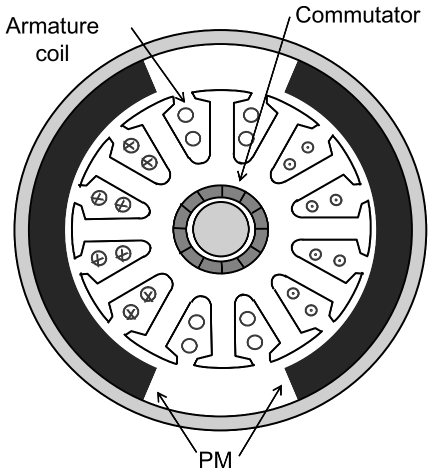

Figure 1.3: Cross section of a typical PM DC motor.

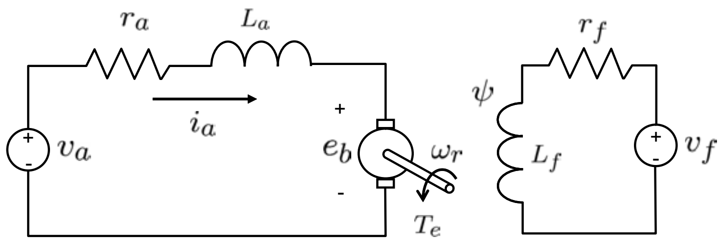

Figure 1.4: Equivalent circuit for a DC motor.

> **Torque generation**: When a current-carrying conductor is placed in a magnetic field, Lorentz force is developed on the conductor. The electromagnetic torque is expressed as $T_e = K_t i_a$, where K_t is the torque constant and i_a is armature current.

An equivalent circuit of a separately wound DC motor is shown in Fig. 1.4. Applying Kirchhoff's voltage law to the equivalent circuit, we obtain

$$v_a = r_a i_a + L_a \frac{di_a}{dt} + e_b, \tag{1.1}$$

$$e_b = K_b \omega_r, \tag{1.2}$$

$$T_e = K_t i_a \tag{1.3}$$

where v_a, i_a, r_a, and L_a are the armature voltage, current, resistance, and inductance, respectively. The back EMF constant, K_b, and torque constant, K_t, depend on the magnet flux developed by the field winding. Fig. 1.4 also shows the field winding circuit, in which the air gap flux is is denoted by ψ. Within a rated speed region, ψ is controlled to be a constant. Obviously, K_b and K_t are proportional to ψ.

Note that the electrical power of the motor is equal to $e_b i_a$, whereas the mechanical power is $T_e\,\omega_r$. From the perspective of power conversion, the electrical power and mechanical power should be the same. Neglecting the power loss by armature resistance, r_a, it follows that $T_e\omega_r = e_b i_a$. Therefore, we obtain $K_t = K_b$.

In the motoring action, a current is supplied to the armature coil from an external source, v_a. As the motor rotates, back EMF, e_b develops. But since $v_a > e_b$, the current flows into the motor ($i_a > 0$), and torque is developed on the shaft. In contrast in the generation mode, an external torque forces the machine shaft to rotate, and the back EMF is higher than the armature voltage, i.e., $v_a < e_b$. Therefore, the current flows out from the machine to the external load ($i_a < 0$). At this time, an opposing torque is developed, leading to mechanical power consumption.

Exercise 1.1
Calculate K_t and K_b for the DC motor whose parameters are listed in Table 1.1.

Solution
The back EMF is equal to $e_b = v_a - r_a i_a = 240 - 16 \times 0.6 = 230.4$ V. Hence, $K_b = e_b/\omega_r = 230.4/127.8 = 1.8$Vsec/rad. Since $K_t = T_e/i_a = 28.8/16 = 1.8$Nm/A, one can check $K_t = K_b$. ■

Table 1.1: Example DC motor parameters

Power (rated)	3.73kW
Voltage (rated)	240V
Armature current (rated)	16A
Rotor speed (rated)	1220rpm (127.8 rad/sec.)
Torque (rated)	28.8Nm
Resistance, r_a	0.6Ω

Exercise 1.2
Consider a DC motor with armature voltage 125V and armature resistance $r_a = 0.4\Omega$. It is running at 1800rpm under no load condition.
a) Calculate the back EMF constant K_b.
b) When the rated armature current is 30A, calculate the rated torque.
c) Calculate the rated speed.

Solution
a) With no load condition, $i_a = 0$. Thus,

$$K_b = \frac{125\text{V}}{1800\text{rpm}} \times \frac{60\text{rpm}}{2\pi\text{rad/sec.}} = 0.663\text{Vsec/rad}.$$

b) Since $K_t = K_b$, $T_e = K_t i_a = 0.663 \times 30 = 19.89$Nm.
c) In the steady-state, $\frac{di}{dt} = 0$. Therefore, $T_e \cdot \omega_r = (v_a - r_a i_a) i_a$. Hence,

$$\omega_r = \frac{(125 - 0.4 \times 30) \times 30}{19.89} = 170.44\text{rad/sec} = 1628\text{rpm}.$$

■

1.1.2 Field-Weakening Control

The back EMF increases as the motor speed increases. The motor is designed such that back EMF e_b reaches the maximum armature voltage, v_a^{max}, at a rated speed, ω_r^{rated}, i.e., $v_a^{max} \approx K_b \omega_r^{rated}$. If the speed is higher than ω_r^{rated}, the source (armature) voltage is not high enough to accommodate the back EMF. Then, the question is how to increase the speed above the rated speed.

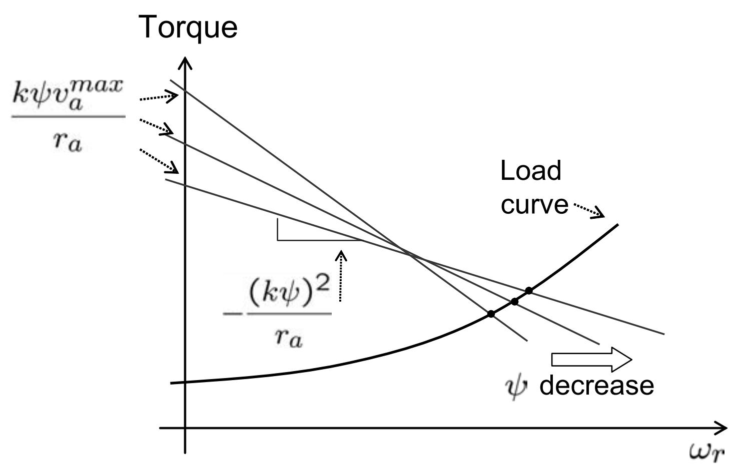

Figure 1.5: Torque curve change with respect to ψ. As ψ decreases, the operational speed increases.

In the steady-state, the armature current is constant. Thus, $L_a \frac{di_a}{dt} \approx 0$. Therefore, in the high-speed region

$$T_e = K_t i_a = K_t \frac{v_a^{max} - K_b \omega_r}{r_a} = \frac{K_t v_a^{max}}{r_a} - \frac{K_t^2}{r_a}\omega_r. \tag{1.4}$$

Note that K_t is proportional to flux, ψ, so that we let $K_t = k\psi$ for some $k > 0$. Then, (1.4) is rewritten as

$$T_e = \frac{k\psi v_a^{max}}{r_a} - \frac{k^2\psi^2}{r_a}\omega_r. \tag{1.5}$$

Obviously, as flux ψ decreases, $k\psi v_a^{max}/r_a$ decreases; whereas the slope $-(k\psi)^2/r_a$ approaches zero. Fig. 1.5 shows three torque-speed curves for different ψ's along