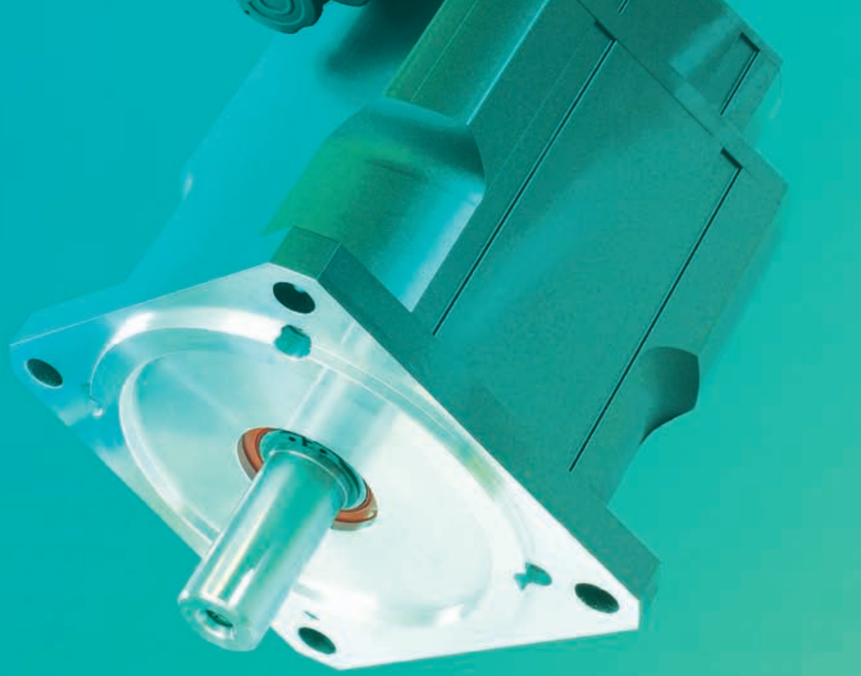

PERMANENT MAGNET BRUSHLESS DC MOTOR DRIVES AND CONTROLS

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Chang-liang Xia
Tianjin University, P.R. China

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Contents

About the Author

Chang-liang Xia was born in Tianjin, China, in 1968. He received his B.S. degree from Tianjin University, China, in 1990, and his M.S. and Ph.D. degrees from Zhejiang University, China, in 1993 and 1995 respectively, all in electrical engineering.

He is currently a Professor in the School of Electrical Engineering and Automation, Tianjin University. In 2008, he became "Yangtze Fund Scholar" Distinguished Professor and is currently supported by the National Science Fund for Distinguished Young Scholars.

His research interests include wind power generation system and intelligent control, motor control and power electronics, novel electric machine and intelligent control, and electrical energy saving control technology. He has published more than 180 papers in these areas. In addition, he has presided over more than 40 scientific research projects as the prime principal of the project. As the first inventor, he holds 13 authorized national invention patents of P. R. C.

In 2011, Prof. Xia was awarded the Second Prize of National Science and Technology Advancement (Rank First) for his work "Study and Application of High-efficiency Machine System Optimal Design under Complicated Constrains." He was also awarded the First Prize of Science and Technology Advancement from Tianjin Province (Rank First) twice, in 2005 and 2008, respectively. In addition, he has awarded the First Prize of Science and Technology Advancement from the National Ministry of Education (Rank First) in 2009.

Prof. Xia is a member of China Electrotechnical Society (CES). He is an editorial member of Transactions of China Electrotechnical Society, and the Advanced Technology of Electrical Engineering and Energy as well. He is also a deputy committee director in Electric Control System and Equipment Committee of CES, Electrical Automation Committee of Chinese Association of Automation, and Sub-committee on Electrical Machinery and Electrical Appliances of the China Machinery Industry Federation. In addition, he is the Vice Chairman of the Tianjin Society of Electrical Engineering.

Preface

In the past five years, the permanent magnet brushless motor market has grown much faster than the other small-motor markets. Thus, it is essential for electrical and electromechanical researchers to stay up-to-date on the latest developments in modern electrical motors and drives, including their control, simulation and hardware implementation.

I have been engaged in the design, modeling, control and application of BLDC motors for more than 15 years. In this field, I have published more than 50 papers in refereed journals and conferences. I have also been an instructor for 6 PhD students and 15 Master's students who have been researching on this subject. This book is an integration of many achievements from the corresponding projects supported by the National Natural Science Foundation of China, Ministry of Education of P. R. C, and the Tianjin Municipal Science and Technology Commission.

Thus, this book is an academic book based on the above research work of the BLDC motor drives over more than a decade. It includes many advances on the control of BLDC motor drives, such as intelligent control, sensorless control, torque ripple reduction, hardware implementation, and so on. Some materials of this book have been used in Tianjin University for the Masters course – "Electrical Motor Drives and Power Electronics" since 2002. In 2009, most of these materials were published in a Chinese book by Science Press, which was entitled *Brushless DC Motor Control Systems*. It has been used as a textbook for the graduate course – "Intelligent Control of Electrical Machines" in Tianjin University since 2009.

In this English edition, new materials have been added to cover the rapid advances of BDLC motor drives. Thus the book is rewritten and organized as follows:

Chapter 1 provides an introduction to the history, current situation and development prospects of BLDC motor drives and control.

Chapter 2 presents the basic principles and the mathematical models of BLDC motors. The related mechanical properties, regulation characteristics and commutation transient process are investigated.

Chapter 3 is devoted to the modeling and control of BLDC motors based on MATLAB. Practical examples are given and analyzed.

Chapter 4 focuses on the analysis of the most important issues related to the speed-control system of BLDC motors, such as the classic double-loop speed-control system, various speed control methods based on modern intelligent algorithms, the influences of the motor internal parameters on system performances, and so on.

One of the most important research directions of BLDC motors, that is the analysis and suppression of torque ripple, is investigated in Chapter 5. The causes and types of torque ripple are analyzed. The cogging torque ripple and its minimization methods are studied. Further, torque ripple reduction approaches based on ADRC, BP neural networks and fuzzy genetic algorithms are presented, respectively.

Sensorless control, another research focus of BLDC motor control systems, is considered in Chapter 6. Based on modern control theory and intelligent algorithm, various types of position-detection methods of BLDC motor and a variety of control methods without position sensors are studied. In addition, different means for motor starting and ways to widen the speed range are proposed.

The software/hardware design approaches and related key technologies for the MCU- and DSP-based BLDC motor control systems are addressed in Chapter 7.

Chapter 8 describes the particular applications of the BLDC motors in elevator doors, elevator traction machines, inverter air conditioners, electric vehicles, electric bicycles, etc.

In addition, questions are supplied at the end of each chapter to facilitate class discussions and as home assignments. Supplementary PowerPoint slides and simulation materials for studying and teaching are provided too. Readers can download them from the book's website (www.wiley.com/go/xia/dcmotor).

In future, permanent-magnet BLDC motor will be used in more applications, especially in those that require a high level of accuracy and performance. Also, key technologies such as sensorless control and torque ripple reduction will be more mature. Thus, this book will allow people who are engaged in the control of BLDC motor drives to gain more knowledge about the principles, simulation and hardware implementation of BLDC motor drives and controls. I hope it will also be useful for other electrical engineers and students who are related to this topic. Some special issues, such as sensorless control, intelligent control, torque ripple reduction and hardware implementation will be valuable for the control of other motors. New progress in power electronics, control theory, and MCU will propel further development of the BLDC motor drives and controls.

This book is intended to be used as a reference book for related technicians in the field of design and control for BLDC motor drives, and a textbook for undergraduates and post-graduates who have learned the following courses: electrical machines, automatic control, motor control, MCU & DSP, and so on.

Over the years, the help and support from Associate Prof. Hong-wei Fang, Associate Prof. Wei Chen, Dr. Qiang Geng, Dr. Yan Yan, Dr. Peng Song and Dr. Ying-fa Wang of Tianjin University have contributed greatly to the success of this book.

Finally, I must also thank my wife Tingna Shi and my son Yuxuan Xia for their love and understanding, without which this task could not have been brought to fruition.

Chang-liang Xia

List of Nomenclature

A	real-time value of torque subsystem during its operation; the electrical load
B	magnetic flux density
B_δ	magnetic load
$B(\theta)$	radial flux density in air gap of PM rotor, which is in trapezoidal distribution along θ
B_m	maximum value of PM density distribution in air gap
B_v	viscous friction coefficient
b_t	stator tooth width
C_i	center vector of Gaussian function at the ith hidden layer unit
$\boldsymbol{C}_j$	center of the jth hidden layer unit that is the closest to the input sample
D_1	diameter of armature; stator outer diameter
$\mathrm{D}_1, \mathrm{D}_2, \ldots\ldots, \mathrm{D}_6$	diodes
D_{i1}	stator inner diameter
d_l	wire diameter of the winding
E	phase back-EMF
E_0	gradient of the sloping part for back-EMF
e_A, e_B and e_C	phase back-EMF of phase A, phase B, and phase C, respectively
e_c	rate of change for motor speed error e
e_i	output error of the ith network
e_L	line back-EMF
e_{max}	largest positive error value in basic domain
e_{sr}	stable error
e_x	phase back-EMF, in which subscript x denote phase A, B and C
e_y	output of the fuzzy controller
$e_{\psi x}$	phase-induced EMF
f	frequency of the back-EMF; fitness of the mutation individuals
f_{avg}	average fitness for per generation population
$f_A(\theta), f_B(\theta), f_C(\theta)$	waveform coefficient of back-EMF
f_i	fitness of ith individual
f_{max}	maximum population fitness
f'	larger fitness in two crossover individuals
f_{st}	starting commutation frequency

f_{xt}	resonator frequency
g	feedback gain coefficient
H_A, H_B, H_C	output signals of Hall position sensors
H	conjugate and transpose symbol
h_m	alnico thickness
I	current amplitude
$\boldsymbol{I}$	phase current matrix
i	steady phase current; detected armature current
i_x	phase current, in which subscript x denote phase A, B and C
i^*	reference current
J	moment of inertia
K	gain constant of the integrator; sliding gain
K_D	differential coefficient
K_I	integral coefficient
K_P	proportional gain
K_{e10}, K_{ec0}, K_{u0}	base values
K_1, K_2, K_3	fine-tuning parameters (all are non-negative)
K_T	torque coefficient
k_e	coefficient of line back-EMF, $k_e = 2p\psi_m = 4pNSB_m$
K_{e1}, K_{ec}	quantization factors
K_{e1}	error quantization factor
K_{ec}	error change quantization factor
K_u	scaling factor
L	inductance; length
L_0	nominal inductance
L_1	stator iron core length
L_A	self inductance of phase A
L_{af}	armature effective length
L_a	equivalent line inductance of winding, $L_a = 2(L - M)$
L'	equivalent phase inductance of winding, $L' = L - M$
M	population size; mutual inductance of phase winding
M_{AB}, M_{AC}, M_{BC}	phase mutual inductance
M_p	system maximum overshoot
$\boldsymbol{M}$	controllability matrix
N	number of winding turns
N_a	peripheral speed
N_r	sampling frequency
n	motor or rotor speed; numbers
n_N	rated speed
n^*	reference speed
P_0	no-load loss, including the core loss and mechanical friction loss
P_2	output power ($P_2 = T_L\Omega$)
P_C	copper loss
P_{Cu}	armature copper loss ($P_{Cu} = r_a I^2$)
P_T	loss of bridge power switches ($P_T = \Delta UI$)
P_{si}	selected probability of the ith individual

P_c	crossover probability
P_e	electromagnetic power ($P_e = k_e \Omega I$)
P_m	mutation probability
P_N	rated power
p	number of conductors in series per phase; number of pole pairs
q	number of slots per phase and per pole
$Q_1, Q_2, \ldots\ldots, Q_6$	instant of phase commutation
R_x	phase resistance, in which subscript x denote phase A, B and C
R_0	stator nominal resistor
$\boldsymbol{R}$	phase winding resistance matrix
r_a	line resistance of winding, $r_a = 2R$
s	switching function
S	product of rotor radius and the effective length of conductors
$S_1, S_2, \ldots\ldots, S_6$	conduction signals
$T_1, T_2, \ldots\ldots, T_6$	power switches
T_0	no-load torque corresponding to no-load loss ($T_0 = P_0/\Omega$)
T_c	cogging torque
T_D	differential time constant
T_e	electromagnetic torque
T_I	integral time constant
T_L	load torque
T_N	rated torque
T_r	rising time of the system response
T_{st}	starting torque
$T(k)$	the kth commutation instant
$\hat{T}_e$	tracking value of electromagnetic torque
T_{b0}	starting friction torque
t_e	time constant
t_s	adjusting time
$\boldsymbol{U}$	phase voltage matrix
U_d	DC bus voltage; DC voltage of the inverter bridge
U_N	neutral to ground voltage of the three phase windings
U_{out}	output voltage of the integrator
u_{sum}	sum of three-phase voltages
U_{th}	threshold
$\triangle U$	voltage drop of the power switches of the bridge inverter
u	number of existed hidden layer unit
u_{AG}, u_{BG}, u_{CG}	phase to ground voltages
u_{AB}, u_{BC}, u_{CA}	line voltages
u_x	phase voltage, in which subscript x denote phase A, B and C
$u(t_0)$	step function
V	electric voltage
V_{CE}	forward voltage of the power switch
V_D	forward voltage of the diode
W_m	energy of air gap electromagnetic filed
w_{ij}	weight between network layers

X_i	N-dimensional input
y_1	polar distance
y_i	network output; actual output of the ith neuron
Z	slots of the armature core
$Z(k)$	moment of the kth zero crossing point
α	momentum factor; learning rate; leading conducting angle
α_{p}	pole arc coefficient
α_{sk}	skewed slot coefficient
β_{01}, β_{02}	coefficients of observer
γ	learning rate
ξ	damping ratio of the second-order system
ε	unmodeled dynamics
η	efficiency of the motor
λ	coefficient of leakage permeance
λ	forgetting factor ($0\leq \lambda \leq 1$)
θ	relative angular displacement between rotor and stator; rotor position angle
θ_{B}	air-gap flux density; platform width of air-gap flux density waveform
θ_{E}	electric angle at the decreasing moment of the line back-EMF
θ_{e}	platform width of overall back-EMF
θ^*	electric angle at the crossing point of the line back-EMF
σ_i	normalized constants of the ith hidden layer unit
δ	air gap; local gradient for weight correction of ith neuron
Λ_{A}	permeance of self-inductance of flux in phase A
Λ_{AB}	permeance of mutual inductance flux between phase A and phase B
ω	electrical angular speed of motor; electricity angle of motor
ω_{k}	weighting coefficient from the hidden layer to the output layer
ω_{n}	natural frequency of the second-order system
ω^*	rotate speed reference signal
$\hat{\omega}$	estimated signal
Ω	mechanical angular speed of the motor
Ω_{r}	reference mechanical angular speed
φ	output function
$\boldsymbol{\Psi}$	matrix of flux linkage
ψ_{f0}	nominal flux
ψ_{m}	magnetic flux linkage of each phase; maximum value of PM flux linkage of each winding, $\psi_{\mathrm{m}} = 2NSB_{\mathrm{m}}$
$\psi_{\mathrm{pm}}(\theta)$	PM flux linkage
ψ_{rotor}	flux of rotor permanent magnet
ψ_{sum}	total flux of each phase
$\Delta_{\mathrm{a}}(s)$	additive perturbation
$\Delta_{\mathrm{i}}(s)$	input multiplicative perturbation
$\Delta_{\mathrm{o}}(s)$	output multiplicative perturbation

1

Introduction

Two typical definitions about the brushless DC motor (BLDC motor, BLDCM) have been presented by scholars. Some of them considered that only the trapezoid-wave/square-wave brushless motors could be called BLDC motors, and sine-wave brushless motors should be called permanent magnet synchronous motors (PMSM) [1,2]. However, other scholars thought that all the motors above should be considered as BLDC motor [3]. ANSI/IEEE Standard 100-1984 has just defined “Brushless Rotary Machinery” [4]. Moreover, in NEMA Standard MG7-1987, a BLDC motor is defined as a type of self-synchronous rotary motor controlled by electronic commutation, where the rotor is a permanent magnet with rotor-position sensors [5], and the related commutation circuit could be either independent or integrated to the motor. So far, there has not been a unified standard about the classification or definition of the BLDC motor. By using the former definition, a BLDC motor is considered in this book as the trapezoid/square wave motor with the starting characteristics of series excitation DC motors and the speed-regulation characteristics of shunt excitation DC motors. It has advantages like simple structure, high efficiency and large torque, etc. Hence, it is widely used in national defense, aerospace, robotics, industrial process control, precision machine tools, automotive electronics, household appliances and office automation. The development history of BLDC motor, its application fields, research status and the development tendency of related technology are presented in this chapter.

1.1 History of BLDC Motors

In the modern society, electricity is the most popular secondary energy source. The application of motors has spread to all kinds of fields in national economy and our daily life as the main mechanic-electronic energy-conversion device for more than a century. In order to adapt to different practical applications, various types of motors, from several milliwatts to millions of kilowatts, including synchronous motors, induction motors, DC motors, switched reluctance motors and so on, emerge as the times require. Although the synchronous motor has advantages of large torque, hard mechanical characteristic, high precision and efficiency, it has difficulties in speed regulation, which limits the range of its application. An induction motor has the advantages of simple structure, easy fabrication, reliable work and low price, but it is uneconomical to regulate the speed smoothly over a wide range and it is not easy to start up.

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Also, it is necessary to absorb the lagging field current from the power system resulting in the decrease of grid power factor. Moreover, its mechanical characteristic is soft and the power factor is small. Without windings or a permanent magnet on its rotor, a switched reluctance motor has a simple structure and low price. It can produce high torque at low speed. However, the noise and torque ripples limit its popularization and applications. DC motors are still widely used in electric power drive systems that have demands for start up and speed regulation, such as electric traction, rolling mill and hoisting equipment, because this type of motors have high efficiency and good speed-regulation performance. Nowadays, DC motors of small capacity are still widely used in automation and control systems. But in traditional DC motors, mechanical commutation is implemented by using brushes, which will result in problems like mechanical friction that would shorten the lifetime, and create noise, electric sparks, and radio interference, etc. In this condition, considering the disadvantages of high production cost and inconvenient maintenance [6–10], the range of applications in particular areas has been limited. Therefore, applications of small and medium size are in urgent need of novel high-performance motors.

The BLDC motor is developed on the basis of brushed DC motors. The modern machine theory was established when Faraday discovered the electromagnetism induction phenomenon in 1831. The first DC motor was born in the 1840s. Confined by the development of power electronic devices and permanent magnet materials, BLDC motor was designed successfully until more than one century later. In 1915, an American, Langmuir, invented the mercury rectifier to control grid electrode and made the DC/AC converter. Contraposing the disadvantages of traditional motors, in the 1930s, some scholars started developing brushless motors in which electronic commutation was implemented, which made preparations for the BLDC motor. However, at that time, power electronic devices were still in the early stage of development, scholars could not find an appropriate commutation device. This type of motor, with less reliable work and low efficiency, was only used in the lab instead of being popularized. In 1955, Harrison and Rye made the first patent claim for a thyristor commutator circuit to take the place of mechanical commutation equipment. This is exactly the rudiment of the BLDC motor [11]. The principles of operation are as follows, when the rotor rotates, periodic electromotive force (EMF) is induced in the signal winding, which leads to the conduction of related thyristors. Hence, power windings feed by turns to achieve commutation. However, the problems are, first, when the rotor stops rotating, induced EMF cannot be produced in the signal windings and the thyristor is not biased, so the power winding cannot feed the current and this type of brushless motor has no starting torque. Furthermore, power consumption is large because the gradient of the electric potential's sloping part is small. To overcome these problems, researchers introduced the commutators with centrifugal plant or put an accessory steel magnet to ensure the motor started reliably. But the former solution is more complex, while the latter needs an additional starting pulse. After that, by numerous experiments and practices, the electronic commutation brushless motor was developed with the help of Hall elements in 1962, which inaugurated a new era in productionization of BLDC motors. In the 1970s, a magnet sensing diode, whose sensitivity is almost thousands of times greater than that of the Hall element, was used successfully for the control of BLDC motor. Later, as the electrical and electronics industry was developing, a large number of high-performance power semiconductors and permanent magnet materials like samarium cobalt and NdFeB emerged, which established a solid ground for widespread use of BLDC motors.

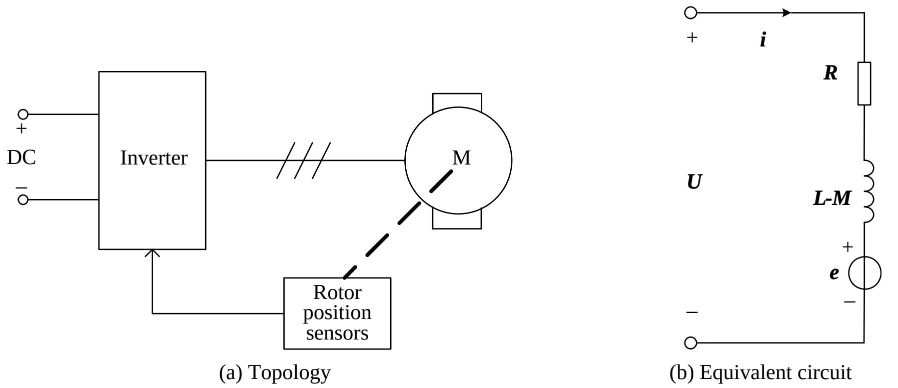

Figure 1.1 Topology and equivalent circuit of BLDC motor.

In 1978, the Indramat branch of Mannesmann Corporation of the Federal Republic of Germany officially launched the MAC brushless DC motor and its drive system on Trade Shows in Hanover, which indicates that the BLDC motor had entered into the practical stage. Since then, worldwide further research has proceeded. Trapezoid-wave/square-wave and sine-wave BLDC motors were developed successively. The sine-wave brushless DC motor is the so-called permanent magnet synchronous motor. Generally, it has the same topology shown in Figure 1.1(a) as that of trapezoid-wave/square-wave brushless DC motors. It can be considered as a PMSM where rotor-position detection is used to control the commutation in order to ensure self-synchronization operation without starting windings. Meantime, these two kinds of motors have the same equivalent circuit as shown Figure 1.1(b), in which L–M is the equivalent inductance of each phase. With the development of permanent magnet materials, microelectronics, power electronics, detection techniques, automation and control technology, especially the power-switched devices like insulated gate bipolar transistor (IGBT), integrated gate-commutated thyristor (IGCT) and so on, the BLDC motors in which electronic commutation is used are growing towards the intelligent, high-frequency and integrated directions.

In the late 1990s, computer techniques and control theories developed rapidly. Microprocessors such as microcontroller units (MCU), digital signal processors (DSP), field programmable gate arrays (FPGA), complex programmable logic devices (CPLD) made unprecedented development, while a qualitative leap was taken in instruction speed and storage space, which further promoted the evolution of BLDC motor. Moreover, a series of control strategies and methods, such as sliding-mode variable structure control, neural-network control, fuzzy control, active disturbance rejection control (ADRC), adaptive control and so on [6,12–20], are constantly used in BLDC motor drive systems. These methods can improve the performance of BLDC motor drive systems on torque-ripple minimization, dynamic and steady-state speed response and system antidisturbance ability to some extent, as well as enlarge the application range and enrich the control theory.

1.2 Applications for BLDC Motors

In recent years, small and medium size motor industries are developing rapidly. About these industries, incomplete statistics of proceeds and volume of sales in China during 2004–2008

Table 1.1 Sales of small and medium electric motor during 2004–2008

Year	2004	2005	2006	2007	2008
Volume of sales (10 k kW)	7847	9702	10950	13009.5	13336
Product revenue (10 k RMB)	1 560 933	2 182 281	2 686 147	3 299 004	3 675 679

are shown in Table 1.1 [21]. In particular, the BLDC motor has achieved a brilliant expansion in automotive, aerospace and household equipment industries, because it has the advantages of high efficiency, long lifetime, low noise and good speed–torque characteristics. Some representative application situations are described as follows.

1.2.1 Automotive BLDC Motor

Automobiles, as a convenient and efficient vehicle, are very close to our daily life. In developed countries, it has a high automobile popularization rate. In China, the automobile industry had been conducted as a pillar industry in industrial policies that was established during the Ninth Five-Year Plan period. In 2007, domestic production was 8 million. There are usually dozens or even hundreds of motors inside an automobile. As the automobile is developing towards energy-saving and environmentally friendly, high-efficiency permanent magnet motors including BLDC motors have a bright future. Some frequently-used performance indexes of motors that are used to drive the electric vehicles are shown in Table 1.2. It can be seen from Table 1.2 that the BLDC motor, which is included in permanent magnet motors, has a good technical superiority [22].

Table 1.2 Comparison between motors used in electric vehicles

Performance index \ Motor type	DC motor	Induction motor	PM motor	Switched reluctance motor
Power density	Low	Intermediate	High	Very high
Peak efficiency (%)	<90	90–95	95–97	<90
Load efficiency (%)	80–87	90–92	85–97	78–86
Controllability	Simple	Complex	Hard for field-weakening	Complex
Reliability	Normal	Good	Excellent	Good
Heat dissipation	Bad	Bad	Good	Good
Size & weight	Big, Heavy	Normal, Normal	Small, Light	Small, Light
High-speed performance	Poor	Excellent	Good	Excellent
Construction	Slightly worse	Better	Slightly better	Excellent
Cost of motor ($/kW)	10	8–10	10–15	6–10
Cost of controller	Low	High	High	Normal
Combination property	Slightly worse	Normal	Excellent	Better

Besides the hardcore of automotive drives, motors can be used on the drives of air conditioners, wiper blades, air bags, electric doors and power seats. Automotive air conditioning is one of the most important accessory products on an automobile, and its performance will change the passengers' comfort directly. Also, it will influence their impression and evaluation about the entire automobile in an indirect way. The motor drive used in automotive air conditioners is often operating with constant load, so it has lower requirements regarding the dynamic response of the system. A motor and its control system have a direct relationship with the performance of automotive air conditioners. Certain key aspects of BLDC motor drives used in automotive air conditioners, has been studied in [23,24]. Similar to the techniques of household air conditioners, air-conditioner compressor driven by a BLDC motor is developing towards more energy-efficient and comfortable directions. As the techniques of power electronics, automation control and computer science are developing, BLDC motor speed-regulation techniques become mature gradually with higher quality and lower price. Therefore, BLDC motors will get a wider range of application, and be a mainstream in speed-regulation techniques.

It is necessary to note that the usage and installation of position sensors would increase the cost of motor drives and affect the reliability and lifetime of the control system. Moreover, automobiles usually have strict restrictions for the volume of the motor. However, sensors are usually installed inside the motors, which will increase the volume. Consequently, the sensorless control strategy will be an important development direction of automotive BLDC motor drive systems.

1.2.2 BLDC Motor in Aerospace

Air-driven and hydraulic-type transmission devices are being replaced by motor-drive equipments, which is a tendency in the aerospace industry. Due to its particular application, in aerospace industry, motors are required to be small size with simple structure. The special structure and position-sensorless control method of BLDC motors make it possible for them to be widely used in aerospace industry. In this condition, the BLDC motor is often operating with variable load, which requests good high-speed regulation and dynamic response, for instance, the application of gyroscopes and robotic arms. It is controlled by using semiclosed or closed-loop speed feedback, where advanced control algorithms are usually implemented in the corresponding systems.

In aerospace, some BLDC motors, such as motors used in high-speed centrifugal pumps and high-speed cameras, could reach the speed of tens of thousands of rev/min or more. Hence, it is necessary to consider the requirements and solutions of mechanical and electrical performance when it operates at high speed. For instance, the bearing problem of a high-velocity rotating motor can be solved by implementing an active magnetic bearing or bearingless design. Moreover, there are significant differences in voltage levels and frequency between universal power and those in aerospace. Therefore, special requirements for rectifier circuits and frequency-conversion drive circuits should be taken into account in BLDC motor control systems, where soft-switching technology can be introduced to minimize the noise and loss during high-frequency switching to improve the properties of the system. Meanwhile, to meet the needs of high reliability, some special means, such as trapping techniques, redundancy techniques and so on, are adopted to prevent software sinking into dead circulation or getting other problems.

1.2.3 BLDC Motor in Household Appliances

Recently, motor drives used in household appliances have increased about 30 per cent every year worldwide. These modern electric appliances are developing towards energy-saving, low-noise, intelligent and high-reliability directions. With the improvement of the living standard of the people and the increasing attention on energy saving and emission reduction from the government, BLDC motors are chosen as the drive motor of household appliances increasingly.

In China, durable consumer goods, air conditioning and refrigerators, whose production has ranked top in recent years throughout the world, have been popularized in cities. Both electric appliances have compressor motors that are usually induction motors. Usually, they have low efficiency and a small power factor and these disadvantages may be overcome by using frequency-conversion technology. Compared with induction motors, BLDC motors have the following advantages: (1) high efficiency; (2) the speed is not limited by power frequency, hence the rated speed can be designed higher, which is beneficial to increasing the capacity and decreasing the size; (3) the power factor is higher, by which the capacity required of the inverter is reduced.

So, if the BLDC motor is implemented in the compressor, it will improve the properties of the compressor significantly and meet the requirements of energy saving and environment protection in modern society. Nowadays, 90 per cent of the induction motors used to drive the compressors have been replaced by BLDC motors in Japan.

Because the compressor motors are sealed, whether in the condition of high or low temperature, position sensors of BLDC motors will influence the reliability of the compressors. The position sensor takes the space inside the compressor, and the signal wires may have an unfavorable influence. Therefore, position-sensorless control is preferable for BLDC motors of the compressor. To reduce the cost and improve the stability of the control system for frequency air conditioning compressors, current commutation signals are acquired by using the back-EMF-based method with a DSP and module IR2316. It achieves the position-sensorless control of BLDC motor for frequency compressor systems, with a motor efficiency of 86 per cent [25]. In addition, position-sensorless control is achieved by implementing the brushless linear DC motor to drive the compressor directly [26]. The transmission mechanism of the eccentric wheel is removed in this system, which is convenient for the design and installation of the compressor. This system, which is suitable for long-stroke linear motion system, is beneficial to reducing the size and the transmission loss, and improving the efficiency.

BLDC motors are also used as the spindle motor drive in VCD, DVD and CD players. Disk-type coreless BLDC motors, which are cheap and usually used in this type of application, have been produced on a large scale. According to different requirements for torque, disk-type BLDC motors as shown in Figure 1.2, can be classified as single-stator type and double-stator type, which is suitable for high-torque drive applications. A product of a DVD/CD player driven by BLDC motor is shown in Figure 1.3.

Moreover, the structure of multipole and external rotors, which is a mature technology, is used in BLDC motors of electric bicycles. BLDC motors used in electric bicycles based on nanotechnology have been designed by a British Company, OLEXI-NANO. Due to its features of high efficiency, low temperature rise, high comfort level and stability, and so on, the comprehensive properties of the electric bicycles are improved. In some areas of household appliances such as vacuum cleaners, agitators, hair dryers, cameras, electric fans and so on, BLDC motors have gradually taken the place of current popular motors that include DC

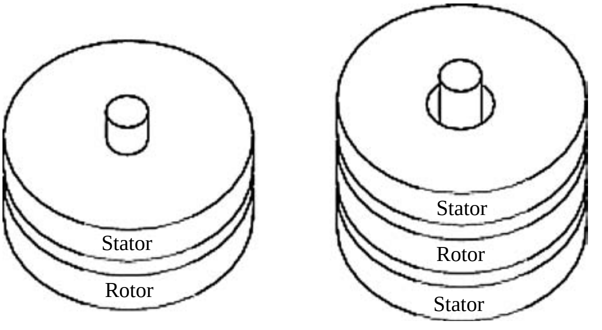

Figure 1.2 Structure of disk-type BLDC motor.

motors, single-phase induction motors and variable-voltage variable-frequency (VVVF) drive induction motors. BLDC motors cannot only overcome some disadvantages of traditional household motors but also reduce the energy loss, which brings a more comfortable lifestyle and properly realizes sustainable energy utilization for people.

1.2.4 BLDC Motor in Office Automation

Most motors used in office automation and computer peripheral equipments are BLDC motors, which is a combination of advanced technology and modern microelectronics. The adoption of the high-performance BLDC motor servosystem improves the quality and increases the value of the products. For example, the BLDC motor used on the main shaft of the hard-disk drives can rotate at high speed with the magnetic disk. The magnetic head, which achieves the executive function for the data on the disk, takes a suspension motion over the surface of the disk about 0.1–0.3 μm to increase the read-write speed. BLDC motors can also be the spindle motor for optical disc and floppy disc drives, and in that case, the BLDC motor has

Figure 1.3 Application of DVD/CD players.

the advantages of low noise, low temperature and high temperature tolerance and it can withstand shock and vibration to a certain extent, which improves the stability of the system. Cooling fans driving motors for computers are usually required to have characteristics such as low noise, compact construction, long lifetime and high speed. Hence, the BLDC motor used in this area adopts an external rotor on which the magnetic steel pieces are usually made of bonded NdFeB. In the area of digital cameras, the BLDC motor has also been widely used. For instance, the Japanese companies Toshiba and Sanyo have both produced the products of BLDC motor drive cameras with the corresponding integrated drive chips TA8479F and LB8632V respectively. With a long history, laser printers driven by BLDC motors are a promising technology and have strong market competitiveness. Its speed can be controlled accurately from thousands of rev/min to tens of thousands of rev/min [27]. Moreover, BLDC motors have good applications in duplicators, facsimiles, recorders, LD video disk players, paper shredders and other office equipments.

1.2.5 BLDC Motor in Other Industries

A BLDC motor control system is an electromechanical integration product that combines the advantages of brushed DC motor and AC asynchronous motor control systems. As the performances of power electronic device and rare-earth permanent magnetic materials are improving and the price is reducing, BLDC motor drive systems, which have increasing applications in industry, has been a main developing direction in the industrial motor drives. Considering performance and cost of the product, famous international motor manufacturers have carried out much research and development. Nowadays, BLDC motors occupy a great portion in civil and military robots and manipulators, where there is a trend that they will take the place of stepping motors and traditional DC servomotors driving robots. High-power BLDC motors also have a good application prospect in some certain occasions, such as low speed, adverse circumstances or where good speed regulation performance is required. For example, in the applications of gearless elevator traction motor drives, pumped storage, transmission of rolling mills, they have the advantages of fast dynamic speed response, small tracking error and static difference ratio, and wide range of speed regulation. Besides the above, practical applications of BLDC motors consist of medical equipments, textile machinery, printing machinery, digital control machine tools, etc.

1.3 Advances in BLDC Motor Drives

Currently, general BLDC motor control is relatively mature and China has developed a specification GJB1863 for it. Research of BLDC motors in developed countries is roughly the same as that in China, whereas the United State and Japan have more advanced manufacturing and control technology. In particular, Japan is more prominent in civil aspects, while the United States is more advanced in the military arena. The current researches mainly focus in the following areas: (1) Develop position-sensorless control technology to improve system reliability and further reduce the motor size and weight. (2) Investigate methods of torque-ripple reduction for BLDC motors, from motor design and control aspects, to improve the servoprecision and expand the scope of application. (3) Design reliable, compact and versatile integrated BLDC motor controllers.

1.3.1 Position-Sensorless Control

The rotor position is directly detected by a position sensor in the traditional method of BLDC motor-position detection, which is called the direct position-detection method. Voltage or current signals of the motor, which are easily acquired, are processed with certain algorithms to get the rotor position signals in the position-sensorless control method, which is also called the indirect rotor-position-detection method. This concept started from the position estimation method by using capacitor shifting, which was proposed by Mieslinger in 1966 [28]. The commonly used indirect rotor-position-detection methods are shown in Figure 1.4.

The back-EMF-based method has a simple principle that is convenient to achieve and is widely used. By using the computer, position-sensorless control was processed in 1985 by Iizuka *et al.* [29] who made comprehensive analysis of software and hardware design for the method, which improved the BLDC motor control to a new level.

During the end of the 1980s to the early 1990s, indirect detection methods of rotor position developed in a diversified trend. Lin *et al.* [30] presented a rotor-position-detection method by using phase current in 1989, considering the principle that if the phase current and the stator flux have the same phase, the rotor position of BLDC motor can be accurately reflected by the change of phase current. In 1990, scholar Ogasawara [31] proposed the inverter switching state estimation method, an ingenious method, which is shown in Figure 1.6 as the freewheeling diode-based method. The basic principle of this method is still the back-EMF-based method, but the EMF is considered from the perspective of current, which is a novel and clever design. Matsui *et al.* [32] presented a detection method for rotor position based on transient current and voltage equations. People began to understand the nature of BLDC motor rotor position variation since the methods were presented in [31,32]. The stator flux-based estimation detection method was proposed in 1994 by Ertugrul *et al.* [33]. In this method, the flux of each stator winding is calculated by the phase voltage and the line current, in order to get the rotor position signal from the flux [33]. Although the computation complexity is higher, the error of this method is less and the range of speed regulation is wider. This method, which is an ideal testing method and has been applied to production, is not only suitable for BLDC motors, but also for PMSM. In the same period, the rotor-position-detection method using a state estimator and a Kalman filter was proposed [34]. Since this method requires a lot of calculations and was limited by the actual conditions at that time, it did not arouse enough attention. In past decades,

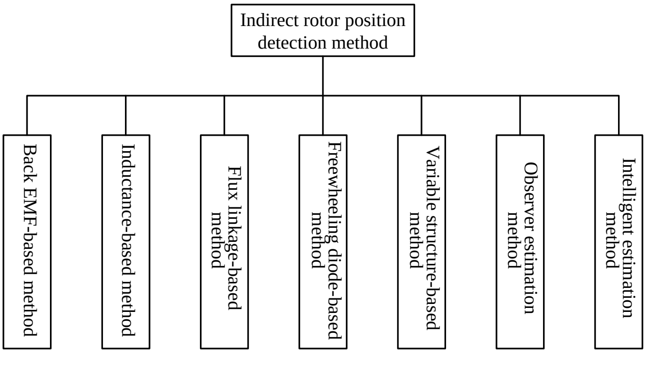

Figure 1.4 Indirect rotor-position-detection methods.

with the improvement of performance of MCU and the upgrading of DSP products, this method has gained rapid development and been applied to actual control systems of BLDC motors [35–37].

The terminal-voltage-based method, an indirect rotor-position-detection method, is actually a changed form of the EMF-based method. It only detects the terminal voltage of each phase, so that the rotor position is acquired through the change of the terminal voltage, whereas the change is actually the reflection for the variation of back-EMF in windings along with the rotor position. However, the terminal-voltage-based method further simplifies the interface circuit, which makes the back-EMF-based method more practical [9,18].

The variable-structure-based method refers to the position-sensorless control that is achieved by making appropriate changes on rotor or stator structure. For instance, adding an auxiliary rotor winding in the surface-mounted-type rotor BLDC motor to get rotor position signals [38], or setting nonmagnetic materials on the rotor surface in order to get the rotor position from detecting the disconnected phase voltage variation caused by eddy-current reaction [39]. In addition, Matsuse *et al.* obtained the rotor position by designing the closed stator slot type motor [40].

As the development of intelligent control is promoting motor control, using fuzzy control, neural networks and other intelligent algorithms to establish the relationship between voltage signals, current signals and rotor position signals is a new approach to position-sensorless detection, which has higher control precision [41–43]. However, compared with traditional position-sensorless control methods, it has more complex algorithms and takes more time in computation, hence the cost is increased.

It is difficult to achieve a direct start for a BLDC motor using position-sensorless control, so the starting mode is always a research focus. The three-step starting technique by using the back-EMF-based method has been more mature. From the start to the stable operation of the motor, this method can be divided into the following three steps: position fixing for rotor, acceleration and switching. Other starting techniques under the position-sensorless control, such as the rotor prelocation method, increasing-frequency and increasing-voltage synchronous methods and the short time measuring pulse rotor orientation starting method, have certain applications.

1.3.2 Torque-Ripple Reduction

Torque-ripple reduction is always an important issue in BLDC motor control systems. As in other motors, some phenomena like the cogging effect and the eddy-current effect cannot be completely avoided in BLDC motor design. Therefore, cogging torque, which should be considered in torque-ripple reduction of BLDC motors, can be restrained with good results by using skewed and fractional slots.

In addition, electronic commutation is usually implemented in BLDC motors, and the presence of motor winding inductance makes it difficult for the phase current to achieve the ideal square-wave current, which may also bring commutation torque ripple to the system. Therefore, to restrain the commutation torque ripple is also an important research, on which many scholars have made a lot of efforts.

The principle of the BLDC motor and the necessity of existence of torque ripple are discussed in [44]. In [45,46], phase voltage and current are transformed with Fourier-series decomposition, and the torque model with fundamental and higher harmonics is derived. Moreover, the purpose