ELECTRIC VEHICLE MACHINES AND DRIVES
ELECTRIC VEHICLE
MACHINES AND DRIVES
DESIGN, ANALYSIS AND APPLICATION

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The University of Hong Kong
To my parents, family, colleagues, and friends worldwide
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Preface

Born in a metropolitan city, I have fully witnessed the decolorization of our blue sky over the past few decades. Hoping to contribute an effort to recover our blue sky, I have devoted myself to researching electric vehicle (EV) technologies for over 20 years–starting from my undergraduate final year project in EV battery monitoring in 1987 to my latest research project in EV in-wheel motor drives in 2014. In fact, EVs have been globally identified to be the greenest road transportation, and the use of EVs will be the most practical way to combat smog and soot from road vehicles in the foreseeable future.

Over the years, there have been many books dealing with EV technologies, mainly briefing various technologies in pure EVs, hybrid EVs, or fuel-cell EVs. Because of the multidisciplinary nature of EV technologies, it is hardly possible to embrace all of them in a single book without sacrificing the latest developments or in-depth discussions. In recent years, some books have begun to deal with specific EV technologies, such as electric propulsion, hybrid propulsion, batteries, and fuel cells. Although many EV machines and drives have been widely published as papers in learned journals, a book comprehensively discussing them is highly desirable. In fact, such advancement of machines and drives is beneficial to the whole EV trio–namely the pure, hybrid, and fuel-cell EVs.

The purpose of this book is to provide a comprehensive discussion on machines and drives for pure electric, hybrid, and fuel-cell vehicles, including both electric propulsion and hybrid propulsion. The corresponding motor drives for electric propulsion range from the existing types, namely the DC, induction, permanent magnet (PM) brushless, and switched reluctance motor drives, to the advanced types, namely the stator-PM, magnetic-geared, vernier PM, and advanced magnetless motor drives. The corresponding machine systems for hybrid propulsion cover the existing types, namely the integrated-starter-generator and planetary-geared electric variable transmission (EVT) systems, and the advanced types, namely the double-rotor EVT and magnetic-geared EVT systems. Meanwhile, emphasis is given to the design criteria, performance analyses, and application examples or potentials of various motor drives and machine systems. It is anticipated that various EVs will adopt different machines and drives, and this book will be a key reference for researchers, engineers, and administrators who need to make such decisions.

While EVs are the driving force for a better environment, my family is the driving power for my work on EVs. Especially, I would like to take this chance to express my heartfelt gratitude to my son, Aten Man-Ho, and my wife, Joan Wai-Yi, for their hearty support all the way.

K.T. Chau
Organization of This Book

This book provides a comprehensive knowledge of electric vehicle (EV) machines and drives, including latest developments and in-depth discussions. It is written for a wide coverage of readers including students, researchers, engineers, administrators, and general readers, and is organized into two themes:

- The first theme is the knowledge of various electric motor drives for EVs, including pure electric and fuel-cell vehicles. It is composed of eight chapters in which Chapters 2–5 deal with those available motor drives for existing EVs, while Chapters 6–9 discuss those advanced motor drives for future EVs.
- The second theme is the knowledge of various electric machine systems for hybrid electric vehicles (HEVs). It consists of four chapters in which Chapters 10 and 11 describe those available machine systems for existing HEVs, while Chapters 12 and 13 elaborate those advanced machine systems for future HEVs.

In this book, there are in total 13 chapters. Each chapter has different numbers of sections and subsections. In order to facilitate selection of reading, all chapters are outlined below:

- Chapter 1 gives an introduction of EVs, including the classification of EVs, overview of EV challenges, and overview of various technologies developed for EVs.
- Chapter 2 is devoted to discussing DC motor drives for EVs, including their system configurations, DC machines, DC-DC converters, and control strategies. The corresponding design criteria, design examples, and application examples are also mentioned.
- Chapter 3 is devoted to discussing induction motor drives for EVs, including their system configurations, induction machines, power inverters, and control strategies. The corresponding design criteria, design examples, and application examples are also discussed.
- Chapter 4 is devoted to discussing permanent magnet (PM) brushless motor drives for EVs, covering both the PM synchronous and PM brushless DC types. Their PM materials, system configurations, PM brushless machines, power inverters, and control strategies are described. The corresponding design criteria, design examples, and application examples are also discussed.
- Chapter 5 is devoted to discussing switched reluctance (SR) motor drives for EVs, including their system configurations, SR machines, SR converters, and control strategies. The corresponding design criteria, design examples, and application examples are also discussed.
- Chapter 6 discusses various stator-PM motor drives for EVs, embracing the doubly-salient PM, flux-reversal PM, flux-switching PM, hybrid-excited PM, and flux-mnemonic PM types. The corresponding design criteria, design examples, and potential applications are also discussed.
- Chapter 7 discusses magnetic-geared (MG) motor drives for EVs, including their system configurations, magnetic gears, MG machines, power inverters, and control strategies. The corresponding design criteria, design examples, and potential applications are also given.
• Chapter 8 discusses vernier PM motor drives for EVs, including their system configurations, vernier PM machines, power inverters, and control strategies. The corresponding design criteria, design examples, and potential applications are also given.
• Chapter 9 discusses various advanced magnetless motor drives for EVs, covering the synchronous reluctance, doubly-salient DC, flux-switching DC, vernier reluctance, doubly-fed vernier reluctance, and axial-flux magnetless types. The corresponding design criteria, design examples, and potential applications are also given.
• Chapter 10 describes integrated-starter-generator systems for HEVs, including their system configurations, machine structures, and operation modes. The corresponding design criteria, design examples, and application examples are also discussed.
• Chapter 11 describes planetary-gear electric variable transmission systems for HEVs, including the system configurations and planetary gears as well as the input-split and compound-split planetary-gear types. The corresponding design criteria, design example, and application examples are also mentioned.
• Chapter 12 describes double-rotor electric variable transmission systems for HEVs, including the system configurations and double-rotor machines as well as the basic and advanced double-rotor types. The corresponding design criteria, design example, and potential applications are also mentioned.
• Chapter 13 describes MG electric variable transmission systems for HEVs, including the system configurations and multi-port magnetic gears as well as the magnetic planetary-gear and magnetic concentric-gear types. The corresponding design criteria, design example, and potential applications are also briefed.

Readers have the flexibility of reading those chapters that are most interesting to them. The suggestion for reading is as follows:

• Undergraduate students taking a course dedicated to EV technologies may be particularly interested in Chapters 1–5 as well as Chapters 10 and 11.
• Postgraduate students taking a course dedicated to advanced EV technologies may be interested in all chapters.
• Researchers in the area of EV machines and drives may be interested in all chapters. Particularly, they may have special interest in Chapters 6–9 as well as Chapters 12 and 13, which involve newly explored research topics.
• Practicing engineers for product design and development may be more interested in Chapters 6–9 as well as Chapters 12 and 13 in which new ideas can be triggered and commercial products can be derived.
• Administrators and general readers may be interested in all chapters. They are advised to read the book from the beginning to the end, page by page, which is most enjoyable.
Acknowledgments

Material presented in this book is a collection of many years of research and development by the author in the International Research Centre for Electric Vehicles and the Department of Electrical and Electronic Engineering at The University of Hong Kong.

I am grateful to all members of my Electric Vehicle Technologies research group, especially Dr. Wenlong Li, Mr. Christopher Ho-Tin Lee, Mr. Mu Chen, Miss Fei Lin, Mr. Zhen Zhang, Mr. Chun Qiu, Dr. Yubin Wang, Dr. Chunhua Liu, Mr. Fuhua Li, Mr. Xianglin Li, and Mr. Feng Yu for their help in the preparation of this book. I want also to express my sincere gratitude to my PhD graduates and postdoctoral fellows, especially Dr. Herman Tsz-Wood Ching, Prof. Ming Cheng, Dr. Ying Fan, Dr. Xiaoyong Zhu, Dr. Wenxiang Zhao, Dr. Shuangxia Niu, Dr. Linni Jian, Dr. Chuang Yu, Dr. Jiangui Li, Dr. Xiaodong Zhang, Dr. Shuang Gao, and Dr. Diyun Wu for their excellent research outcomes, which are essential ingredients of this book.

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Last but not least, I thank my family for the unconditional support and absolute understanding during the writing of this book.
About the Author

K. T. Chau received his B.Sc. (Eng.) degree with First Class Honors, M.Phil., and PhD, all in Electrical and Electronic Engineering from The University of Hong Kong. He joined the alma mater in 1995 and currently serves as Professor in the Department of Electrical and Electronic Engineering, Director of International Research Centre for Electric Vehicles, and Director of B.Eng. degree in Electrical Engineering.

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His teaching and research interests are electric and hybrid vehicles, electric machines, and drives, as well as clean and renewable energies. In these areas, he has published over 400 refereed technical papers, and many industrial reports. His teaching and research philosophy follows the Confucian classic “Li Ji” – Teaching and learning (research) are mutually motivating.

He has received many awards, including the Chang Jiang Chair Professorship; the Environmental Excellence in Transportation Award for Education, Training, and Public Awareness; the Award for Innovative Excellence in Teaching, Learning, and Technology; and the University Teaching Fellow Award.
Introduction

With ever-increasing concern on energy diversification, energy efficiency, and environmental protection, electric vehicles (EVs), including pure electric vehicle (PEV), hybrid electric vehicle (HEV), and fuel-cell electric vehicle (FEV) are becoming attractive for road transportation. Although some of them have become commercially available, there are many challenges and hence opportunities for EV research and development.

In this chapter, the classification of EVs is discussed. Then, an overview of EV challenges is given. Consequently, an overview of various technologies developed for EVs is brought forward.

1.1 What Is an Electric Vehicle?

EVs are nothing new; they were invented 178 years ago but lost the competition for dominance to internal combustion engine vehicles (ICEVs). Actually, the first EV was a battery-powered tricycle built by Thomas Davenport in 1834 (Wakefield, 1994). In 1900, among an annual sale of 4200 automobiles in the US, 38% were EVs, 22% ICEVs, and 40% steam-powered vehicles. At that time, EVs were the preferred road transportation among the wealthy elite. Their cost was equivalent to a Rolls Royce of today. A man with an idea that finished off the EVs for good was Ford. His mass-produced Ford Model T could offer a range double or triple that of the EVs but at only a fraction of their cost. By the 1930s, the EVs almost vanished from the scene. The rekindling of interests in EVs started at the outbreak of the energy crisis and oil shortage in the 1970s. Owing to the growing concern over air quality and the possible consequences of the greenhouse effect in the 1980s, the pace of EV development was accelerated.

In general, EVs are classified as the PEV, HEV, and FEV types on the basis of their energy sources and the propulsion devices (Chan and Chau, 2001; Chau, 2010, 2014). In essence, the PEV is purely fed from electricity, while the propulsion is solely driven by the electric motor; the HEV is sourced from both electricity and gasoline/diesel, while the propulsion involves both the electric motor and engine; and the FEV is directly or indirectly sourced from hydrogen, while the propulsion is solely driven by the electric motor. Moreover, in order to distinguish the refueling means, the HEV can be further categorized into the conventional HEV and the gridable HEV. The conventional one is solely refueled with gasoline/diesel in filling stations, whereas the gridable one can be recharged by electricity via charging ports. On the basis of the hybridization level and the operation feature between the electric motor and engine, the conventional HEV can be further split into the micro HEV, mild HEV, and full HEV. Meanwhile, on the basis of the coordination between the electric motor and engine, the gridable HEV can be further split into the plug-in hybrid electric vehicle (PHEV) and range-extended electric vehicle (REV). This classification is depicted in Figure 1.1.
Deriving from crude oil, the gasoline and diesel are the major liquid fuels for ICEVs. EVs are an excellent solution to rectify this unhealthy dependence because electricity can be generated by almost all kinds of energy resources. Figure 1.2 illustrates the merit of energy diversification due to the use of EVs in which electricity can be produced by thermal power (oil, natural gas, and coal), nuclear power, hydropower, wind power, solar power, oceanic power, geothermal power, and biomass power. In order to compare the overall energy efficiency of EVs with that of ICEVs, their energy conversion processes from crude oil to road load are depicted in Figure 1.3, indicating that EVs are more energy efficient than ICEVs. Moreover, EVs can recover the kinetic energy during braking and utilize it for battery recharging, whereas ICEVs wastefully dissipate this kinetic energy as heat in the brake discs. With this regenerative braking technology, the energy efficiency of EVs can be further boosted by up to 10%.

In many metropolises, ICEVs are responsible for more than 50% of harmful air pollutants and smog-forming compounds. To reduce air pollution from road transportation, the use of EVs is the
most viable choice. Definitely, most EVs offer zero roadside emissions. Even taking into account the emissions from refineries to produce gasoline for ICEVs and the emissions from power plants to generate electricity for EVs, the overall harmful emissions of EVs are still much lower than those of ICEVs as indicated in Figure 1.4, where carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOₓ), sulfur oxides (SOₓ), and particulate matters (PMₓ) are taken into account (Chau, 2010). It should be noted that the overall carbon dioxide (CO₂) emission can also be reduced by about 5% with the use of EVs and energy-efficient power plants. This improvement may be further increased when incorporating with higher percentages of clean or renewable power generation, but may even be negative when adopting inefficient coal-fired power plants.

Currently, the conventional HEV has been commercially available and widely accepted as an energy-efficient and environment-friendly vehicle, while the PEV is becoming commercially available and tagged with a zero-emission label. Nevertheless, there are many challenges and opportunities for EV research and development.

1.2 Overview of EV Challenges

There are different types of EVs, including the PEV, conventional HEV, PHEV, REV, and FEV. These EVs can be grouped into the PEV, HEV, gridable HEV, and FEV for discussion, with emphasis on their challenges (Chau, 2012).

Figure 1.4  Overall harmful emissions of EVs
1.2.1 Pure Electric Vehicle

The PEV, loosely termed the EV, offers the definite advantages of zero roadside emissions and minimum overall emissions (taking into account the emissions due to electricity generation by power plants). Its major challenges are limited driving range, high initial cost, and lack of charging infrastructure.

Currently, the PEV relies on using batteries as their sole or major energy storage device to store electricity even though there is an option to use ultracapacitors as the sole energy storage device. Thus, the PEV is sometimes named as the battery electric vehicle (BEV). At the present status of battery technology, the energy storage capacity of PEVs is far less than that of ICEVs. Typically, for a passenger car under urban driving with air-conditioning, a PEV can travel about 120 km per charge, whereas an ICEV can offer about 500 km per refuel. With such a short driving range per charge, the PEV will suffer from the problem of range anxiety. That is, the PEV driver dare not utilize the remaining capacity such as 20% to travel a trip of 24 km. It should be noted that some PEV models purposely install three to four times the battery capacity to enable their driving range comparable with that of ICEVs, hence solving the short range and range anxiety problems. Of course, these PEV models will be two to three times more expensive than general PEVs, which are actually not targeted for general buyers.

With similar performance, a general PEV is two to four times more expensive than an ICEV. Such high initial cost is because a large number of batteries are necessary to provide a reasonable driving range per charge. Typically, the battery cost accounts for 30–40% of the overall PEV cost. Moreover, the battery life can generally last for about 1500 cycles, which is equivalent to about 4–5 years of vehicle operation, indicating that all batteries of the PEV need to be renewed in the midway of the vehicle life. Thus, the effective cost of the PEV is further higher than the initial cost.

Differing from the ICEV, the PEV takes time for battery charging. The corresponding charging period normally ranges from 5 to 8 hours based on a battery charger with the specifications of 110–240 V, 13–40 A, and 2–4 kW. This charging period is too long for the PEV to provide continuous operation. When adopting the fast or quick charging technique, it takes about 20–30 minutes to charge the batteries up to 80% capacity based on a battery charger with the specifications of 200–400 V, 100–200 A, and 50 kW. Although this charging speed is acceptable for continuous vehicular operation, the installation cost and establishment cost of these fast charging stations are very high. Since the power demand for fast charging is high, the fast charging process inevitably causes burden to our existing power system, which violates the merit of using the PEV for load leveling or demand side management. In case the PEV allows for battery swapping, namely replacing the discharged batteries with the fully charged ones using mechanical means, it takes only a few minutes to mechanically charge up the batteries. Although the time required for battery swapping is comparable to that for gas refueling, the necessary space for each swapping station is much larger. Practically, it involves two implementation challenges: the battery size and location inside the PEV have to be standardized and the single ownership of all batteries needs a new business model.

1.2.2 Hybrid Electric Vehicle

The HEV, loosely termed the hybrid vehicle, refers to the conventional or nongridable version (Chau and Wong, 2002). For the micro HEV, the conventional starter motor is eliminated, while the conventional generator is replaced by an integrated starter-generator (ISG). Instead of propelling the vehicle, the ISG offers two important hybrid features. One feature is to shut down the engine whenever the vehicle is at rest, the so-called idle stop-start feature, hence improving the fuel economy for urban driving. Another feature is to recharge the battery primarily during vehicle deceleration or braking, thus offering a mild amount of regenerative braking. For the mild HEV, the ISG is generally placed between the engine and the transmission. This ISG not only provides the hybrid features of idle stop-start and regenerative braking but also assists the engine to propel the vehicle, thus allowing for a downsized engine (Liu, Chau, and Jiang, 2010a). However, since the engine and the ISG share the same shaft, it cannot offer electric launch
(initial acceleration under electric power only). For the full HEV, the key technology is the electric variable transmission (EVT) system, which mainly functions to perform power splitting. This EVT can offer all hybrid features, including the electric launch, idle stop-start, regenerative braking, and engine downsizing. Compared with the PEV, the HEV can offer a comparable driving range of the ICEV and use the existing refueling infrastructure of the ICEV, but sacrificing the merits of zero roadside emissions and energy diversification. Its key challenges are how to reduce the system complexity that involves both an electric motor and an engine for propulsion and how to coordinate these two propulsion devices to achieve optimal efficiency operation (Chau and Wong, 2002). The turning point of HEV development was the advent of Toyota Prius in 1997 (Hermance and Sasaki, 1998), which initially adopted the EVT system. The key is to employ a planetary gear for power splitting of the engine output power, one via the ring gear to the driveline shaft while one via the sun gear to the generator, then back-to-back converters, motor, and finally the driveline shaft. Hence, under varying road load, the engine can always operate at its most energy-efficient or optimal operation line (OOL), resulting in a considerable reduction in fuel consumption. However, this EVT system suffers from the reliance on planetary gearing, which involves transmission loss, gear noise, and regular lubrication. In addition, the overall system is relatively heavy and bulky.

1.2.3 Gridable Hybrid Electric Vehicle

The term “gridable” means that the vehicle can be directly connected to the power grid. Therefore, the gridable HEV refers to the vehicles that have gridable capability and HEV features, namely the PHEV and REV. The PHEV is extended from the conventional HEV by incorporating the additional feature of plug-in rechargeable. Since it incorporates a larger bank of batteries that can be recharged by plugging into an external charging port, it can offer a longer electric drive range and hence reduce the requirement of refueling from gas stations. On the other hand, the REV is extended from the PEV by incorporating a small engine coupled with a generator to recharge the battery bank. This avoids the range anxiety problem that is always associated with the PEV. Therefore, it can offer energy-efficient operation throughout its electric drive range and hence significantly reduce refueling from gas stations. Although the PHEV and REV are both a HEV and have similar electric motor and battery ratings, they have different nominal operations. The PHEV generally operates in the blended mode in which the electric motor and the engine are coordinated to work together in such a way that the engine can maintain efficient operation, hence achieving high fuel economy. If necessary, it can operate in the pure-electric mode. In contrast, the REV generally operates in the pure-electric mode all the way, regardless of the driving range or profile. Until the battery pack is depleted to the threshold, it can operate in the extended mode that the engine is turned on, which then drives the generator to produce the desired electricity.

The key challenges of the gridable HEV are the system complexity and high initial cost. Its system complexity is similar to that of the conventional HEV, mainly because of the use of both the electric motor and engine. Differing from the conventional HEV, it needs to install the on-board charger to plug in the power grid for battery charging. Its initial cost is much higher than that of the conventional HEV because of the use of a large number of batteries for the pure-electric mode. Of course, when the PHEV operates at the blended mode or the REV operates at the extended mode, they lose the merit of zero roadside emissions.

1.2.4 Fuel-Cell Electric Vehicle

The FEV, loosely termed the fuel-cell vehicle, offers the same advantages as the PEV, namely, zero roadside emissions and minimum overall emissions (taking into account the emissions due to hydrogen production by chemical plants or an on-board reformer). In addition, it can offer a driving range comparable to that of the ICEV. Its major challenges are the high initial cost and lack of hydrogen refueling infrastructure. The high initial cost is because of the use of expensive fuel cells. Hydrogen refueling
infrastructure is generally absent in our society, and the establishment of such an infrastructure involves a huge investment cost. There are three practical ways to store hydrogen in the FEV: the compressed hydrogen gas (CHG), liquid hydrogen (LH), and metal hydride (MH). When adopting the CHG (a pressure of about 350–700 bar) for the FEV, the infrastructure is similar to that of compressed natural gas (a pressure of about 200–248 bar) for some alternative fuel vehicles. When adopting the LH, the infrastructure is very demanding since the hydrogen needs to be cooled to about −253 °C while still pressurized. This requires cryogenic storage technology, which is even more severe than liquid oxygen. When adopting the MH, it needs to have a similar infrastructure as battery swapping to mechanically replace the discharged MH with the fully charged MH. In addition, it requires more energy for providing necessary temperatures (120–200 °C) to discharge the hydrogen and necessary pressure (over 700 bar) to recharge the hydrogen. Both the CHG and LH enjoy the merit of high specific energy (good energy density by weight), which is desirable for the FEV, but also face the same safety concern, which can be an explosion hazard. Meanwhile, the MH takes the merit of safety, which is essential for the FEV, but suffers from the problem of low specific energy, which deteriorates the driving range.

In the coming future, the commercialization of the FEV depends on whether there will be a breakthrough in fuel-cell technology in terms of cost per kilowatt and whether there will be a mandate or energy policy to establish the hydrogen refueling infrastructure.

1.3 Overview of EV Technologies

An overview of key technologies for various types of EVs is presented, with emphasis on their emerging research activities. Among them, the motor drive technology is most actively developed in recent years where there are many innovations and advancements in the design, analysis, and control of motor drives. The energy source technology is also actively developed in recent years. Nevertheless, there is no real breakthrough in the battery technology, especially aspiring the simultaneous possession of low initial cost and high specific energy. Rather than waiting for a breakthrough in battery technology, the battery charging technology is being actively developed. Particularly, the concept of move-and-charge (MAC) for battery charging using wireless power transfer (WPT) is promising to fundamentally solve the long-term shortcomings of EVs. Moreover, in order to promote the advantage of EVs to justify their high initial cost, the vehicle-to-grid (V2G) technology is being actively researched, which can expand the role or function of EVs to increase their cost effectiveness.

1.3.1 Motor Drive Technology

Motor drives are the core technology for EVs that convert the on-board electrical energy to the desired mechanical motion. Meanwhile, electric machines are the key element of motor drive technology. The requirements of electric machines for EVs are much more demanding than that for industrial applications. These requirements are summarized as follows (Zhu and Howe, 2007; Chau, 2009):

- High torque density and high power density
- Wide speed range, covering low-speed creeping and high-speed cruising
- High efficiency over wide torque and speed ranges
- Wide constant-power operating capability
- High torque capability for electric launch and hill climbing
- High intermittent overload capability for overtaking
- High reliability and robustness for vehicular environment
- Low acoustic noise
- Reasonable cost
When the electric machine needs to work with the engine for various HEVs, there are some additional requirements:

- High-efficiency power generation over a wide speed range
- Good voltage regulation over wide speed generation
- Capable of being integrated with the engine

Figure 1.5 shows the classification of electric machines for EVs in which the bold types are those that have been applied to EVs, including the series DC, shunt DC, separately excited DC, permanent magnet (PM) DC, cage-rotor induction, PM brushless AC (BLAC), PM brushless DC (BLDC), and switched reluctance (SR) machines. Basically, EV machines are classified into two main groups: commutator and commutatorless. The former simply denotes that they have a commutator and carbon brushes, while the latter have neither commutator nor carbon brushes. It should be noted that the trend is focused on developing new types of commutatorless or brushless machines (Chau, Chan, and Liu, 2008), especially the class of doubly salient machines and the class of vernier machines.

The key feature of doubly salient machines is the presence of salient poles in both the stator and rotor. The SR machine is a kind of doubly salient machines having the simplest structure. When incorporating PMs in the stator of doubly salient machines, a new class of PM brushless machines is resulted—the stator-PM machine (Liu et al., 2008). Since the rotor has neither PMs nor windings, this class of machines is mechanically simple and robust, hence very suitable for vehicular operation. According to the location of the PMs, it can be split into doubly salient permanent magnet (DSPM), flux-reversal permanent magnet (FRPM), and flux-switching permanent magnet (FSPM) machines. Additionally, with the inclusion of independent field windings in the stator for flux control, the class can be further split into the flux-controllable (FC) types—the FC-DSPM, FC-FRPM, and FC-FSPM. Furthermore, when the PM poles are replaced with DC field windings aiming to get rid of those expensive PM materials and provide flexible flux control, the resulting doubly salient DC (DSDC), flux-reversal DC (FRDC), and flux-switching DC (FSDC) machines are emerging types of advanced magnetless machines.

The key feature of vernier machines is the use of vernier effect to amplify the output torque while stepping down the speed, leading to be a class of brushless machines dedicated to low-speed high-torque direct-drive application. There are two main classes of vernier machines: vernier permanent magnet (VPM) and vernier reluctance (VR). There are three types of VPM machines depending on the location...
of PMs: the rotor-PM type with all PMs mounted on the rotor, the stator-PM type with all PMs mounted on the stator, and the all-PM type with PMs mounted on both the rotor and stator. As the rotor-PM VPM machine is most mature, it is loosely called as the VPM machine (Li, Chau, and Li, 2011). The stator-PM VPM machine is commonly termed the vernier hybrid machine (Spooner and Haydock, 2003). On the other hand, the VR machine is structurally similar to the SR machine, but they operate differently. In essence, the VR machine is fed by three-phase sinusoidal currents to produce the rotating magnetic field, and the rotor runs synchronously at a fraction of the speed of this rotating field (Lee, 1963). Because of its inherently low power factor, an additional supply can be incorporated to feed an additional field winding in the stator of the VR machine, thus resulting in the doubly fed vernier reluctance (DFVR) machine (Taibi, Tounzi, and Piriou, 2006). This additional field winding can be fed by AC or DC current, leading to further create the vernier reluctance AC (VRAC) and vernier reluctance DC (VRDC) machine. The VR and DFVR machines are also classified as emerging types of advanced magnetless machines.

All EV machine topologies developed for the conventional radial-flux morphology can readily be extended to other morphologies such as the axial-flux morphology (Lee, Liu, and Chau, 2014), linear-flux morphology (Du et al., 2011), and transverse-flux morphology (Wang et al., 2008). The axial-flux morphology takes the advantages of higher power density and higher torque density than its radial-flux counterpart, but suffers from the problem of large axial force exerted on the stator by the rotor and limited to pancake shape. As the linear-flux morphology functions to provide linear motion, it is less attractive for EV propulsion. Although the transverse-flux morphology can offer the highest torque density, the corresponding machine structure is very complicated, which limits its manufacturability and practicality for EVs.

Apart from developing EV motor drives for pure electric propulsion, namely for the PEV and FEV, the technological development of EV machines has been extended to hybrid propulsion for HEVs. As depicted in Figure 1.6, there are two main machine systems for hybrid propulsion: the ISG system for the micro and mild hybrids and the EVT system for the full hybrid (Chau and Chan, 2007). The ISG system needs to offer not only the conventional features of engine cranking and electricity generation, but also the hybrid features of idle stop-start, regenerative braking, and power assistance. Therefore, the corresponding machine design, analysis, and control are very demanding (Liu, Chau, and Jiang, 2010a). The EVT functions to offer electrically controllable power transfer from the engine to the wheels with continuously variable transmission, hence providing all hybrid features including the electric launch, idle stop-start, regenerative braking, and power assistance, as well as achieving the highest fuel economy. There are three main types of EVT systems: the planetary-gared electric variable transmission (PG EVT), double-rotor electric variable transmission (DR EVT), and magnetic-gared electric variable transmission (MG EVT). The PG EVT system is almost exclusively used for the commercially available full hybrid, which was first developed by Toyota for its Prius (Kamiya, 2006). However, this PG EVT system inherits the fundamental drawbacks of planetary gearing, namely the transmission loss, gear noise, and need for regular lubrication. In recent years, the concept of double-rotor machines has been developed, which can be used to supersede the planetary gearing, hence forming the gearless DR EVT system (Hoeijmakers and Ferreira, 2006). However, this DR EVT system needs to employ slip rings and carbon brushes to extract the energy from the inner rotor, which suffers from the reliability concern and need for regular maintenance.

Figure 1.6 EV machine systems for HEVs